



(12) **United States Patent**  
**Hafner et al.**

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(54) **TRAILER BACKUP ASSIST SYSTEM WITH TRAJECTORY PLANNER FOR MULTIPLE WAYPOINTS**

(71) Applicant: **Ford Global Technologies, LLC**,  
Dearborn, MI (US)  
(72) Inventors: **Michael Hafner**, Ann Arbor, MI (US);  
**Thomas Edward Pilutti**, Ann Arbor, MI (US)

(73) Assignee: **Ford Global Technologies, LLC**,  
Dearborn, MI (US)

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(22) Filed: **Apr. 21, 2014**

(65) **Prior Publication Data**

US 2014/0303849 A1 Oct. 9, 2014

**Related U.S. Application Data**

(63) Continuation-in-part of application No. 14/256,427, filed on Apr. 18, 2014, which is a continuation-in-part of application No. 14/249,781, filed on Apr. 10, 2014, which is a continuation-in-part of application No.

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(51) **Int. Cl.**  
**B62D 6/00** (2006.01)  
**B62D 13/06** (2006.01)

(Continued)

(52) **U.S. Cl.**  
CPC ..... **B62D 13/06** (2013.01); **B60D 1/245** (2013.01); **B60D 1/62** (2013.01); **B60W 30/00** (2013.01); **B62D 15/027** (2013.01); **H04N 7/183** (2013.01)

(58) **Field of Classification Search**

CPC ..... B62D 13/06; B62D 15/027; B62D 12/02; B62D 15/028; B62D 15/0285; B62D 1/00; B62D 6/002

USPC ..... 701/42

See application file for complete search history.

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*Primary Examiner* — Thomas G Black

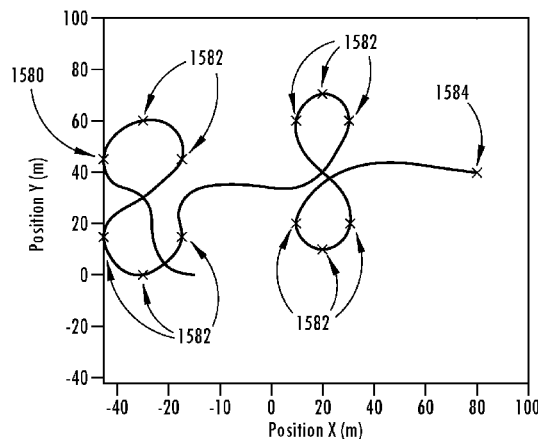
*Assistant Examiner* — Sze-Hon Kong

(74) *Attorney, Agent, or Firm* — Raymond Coppiellie; Price Heneveld LLP

(57) **ABSTRACT**

A trailer backup assist system, according to one embodiment, includes a state estimator that determines a current position of a trailer relative to a plurality of waypoints. A trajectory planner may then incrementally generate a path from the current position to the plurality of waypoints. The trajectory planner has a first mode that generates first and second circular trajectories tangent to one another connecting between the current position and a waypoint of the plurality of waypoints. A second mode of the trajectory planner generates the second circular trajectory between the current position and the waypoint after the trailer traverses the first circular trajectory. Also, a third mode of the trajectory planner switches to the first operating mode when the trailer reaches the waypoint for guidance to a subsequent waypoint. A curvature controller guides the trailer based on a curvature of the respective first or second circular trajectories.

**20 Claims, 64 Drawing Sheets**



**Related U.S. Application Data**

14/188,213, filed on Feb. 24, 2014, which is a continuation-in-part of application No. 13/847,508, filed on Mar. 20, 2013, and a continuation-in-part of application No. 14/068,387, filed on Oct. 31, 2013, now Pat. No. 9,102,271, which is a continuation-in-part of application No. 14/059,835, filed on Oct. 22, 2013, which is a continuation-in-part of application No. 13/443,743, filed on Apr. 10, 2012, now Pat. No. 8,825,328, which is a continuation-in-part of application No. 13/336,060, filed on Dec. 23, 2011, now Pat. No. 8,909,426, said application No. 14/249,781 is a continuation-in-part of application No. 14/161,832, filed on Jan. 23, 2014, which is a continuation-in-part of application No. 14/059,835, filed on Oct. 22, 2013, and a continuation-in-part of application No. 14/201,130, filed on Mar. 7, 2014, which is a continuation-in-part of application No. 14/068,387, filed on Oct. 31, 2013, now Pat. No. 9,102,271.

(60) Provisional application No. 61/477,132, filed on Apr. 19, 2011.

**(51) Int. Cl.**

**B62D 15/02** (2006.01)  
**B60W 30/00** (2006.01)  
**H04N 7/18** (2006.01)  
**B60D 1/24** (2006.01)  
**B60D 1/62** (2006.01)

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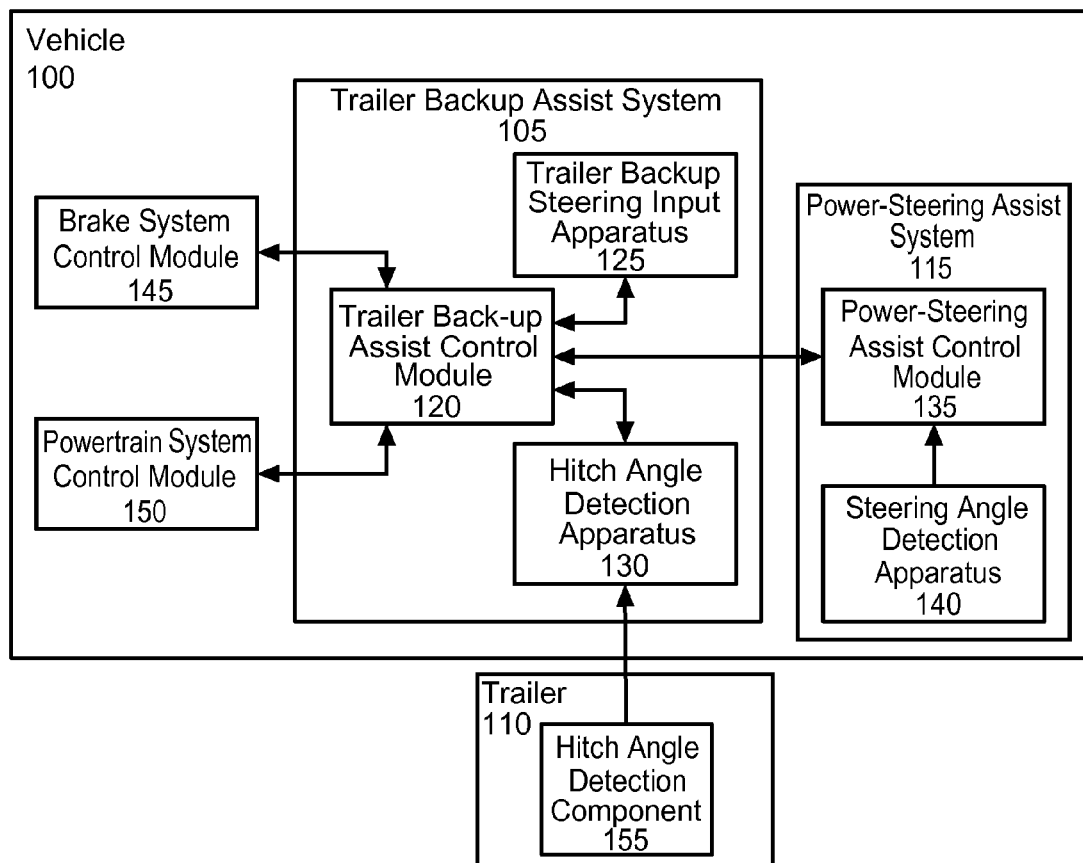
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**FIG. 1**

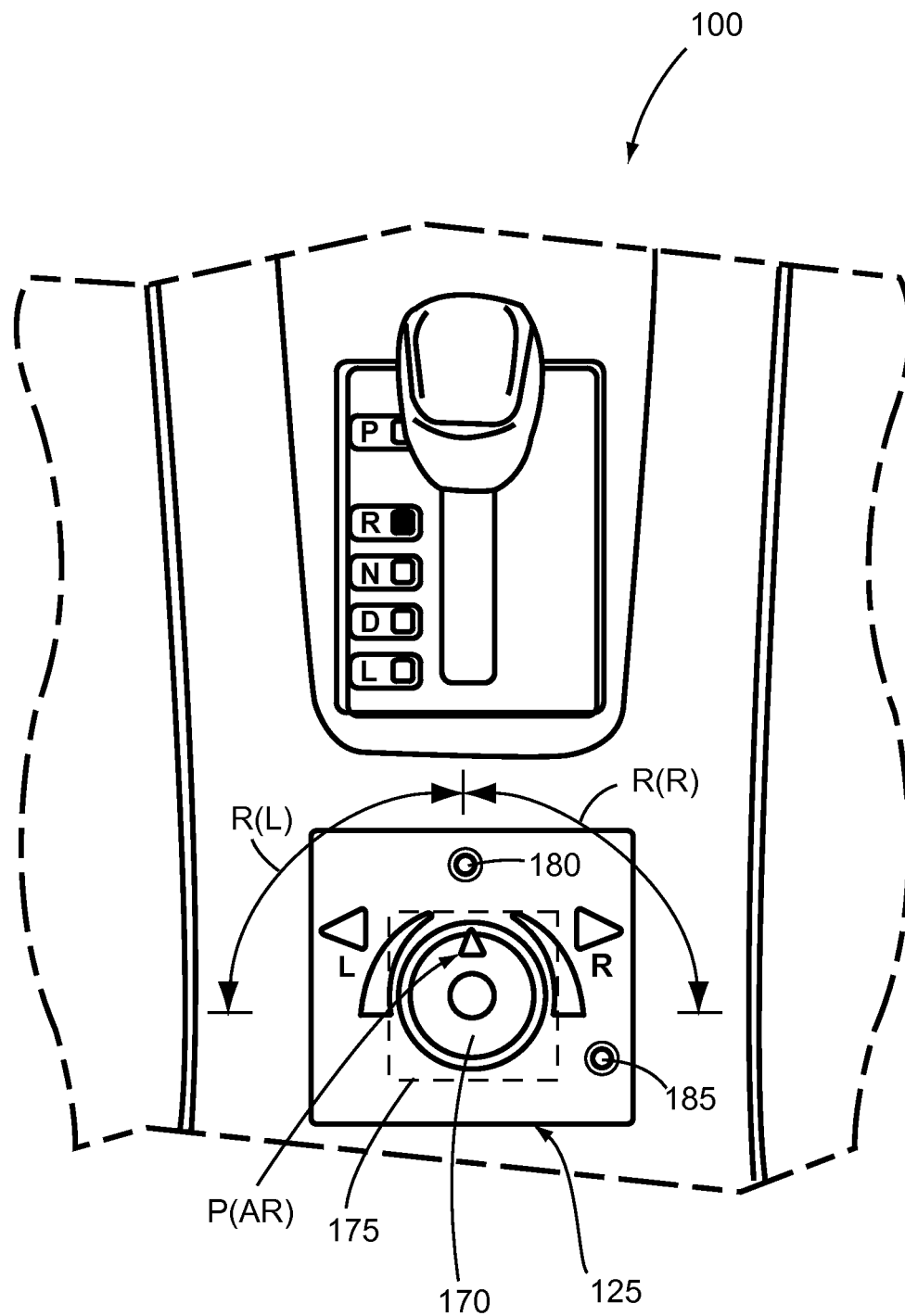
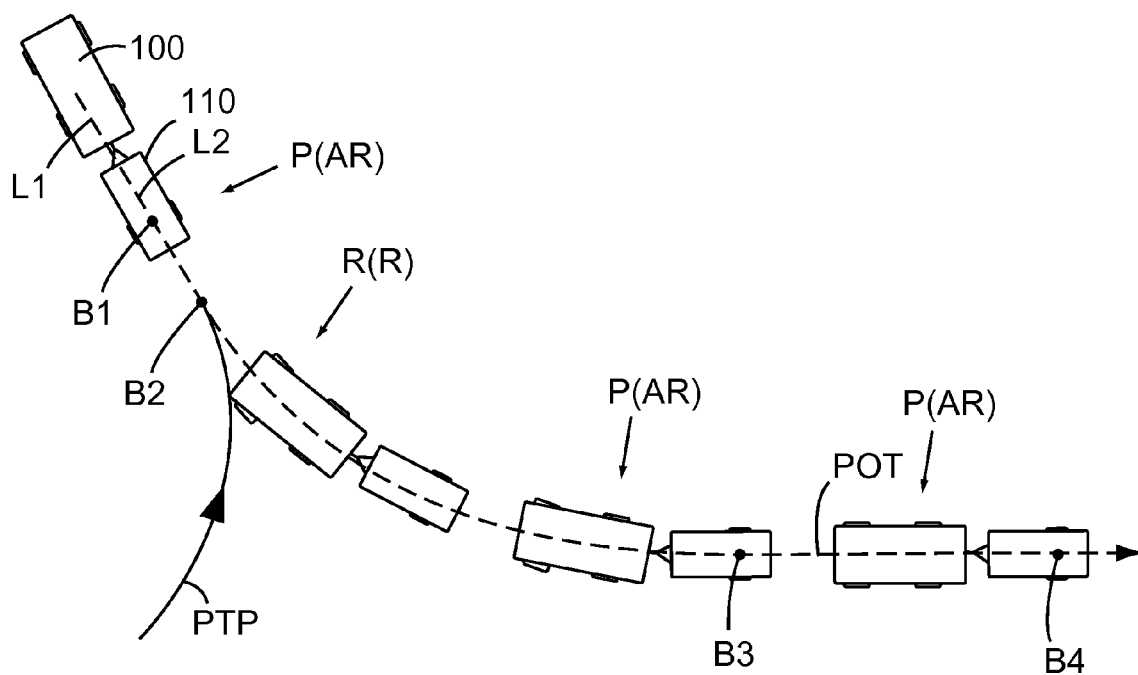
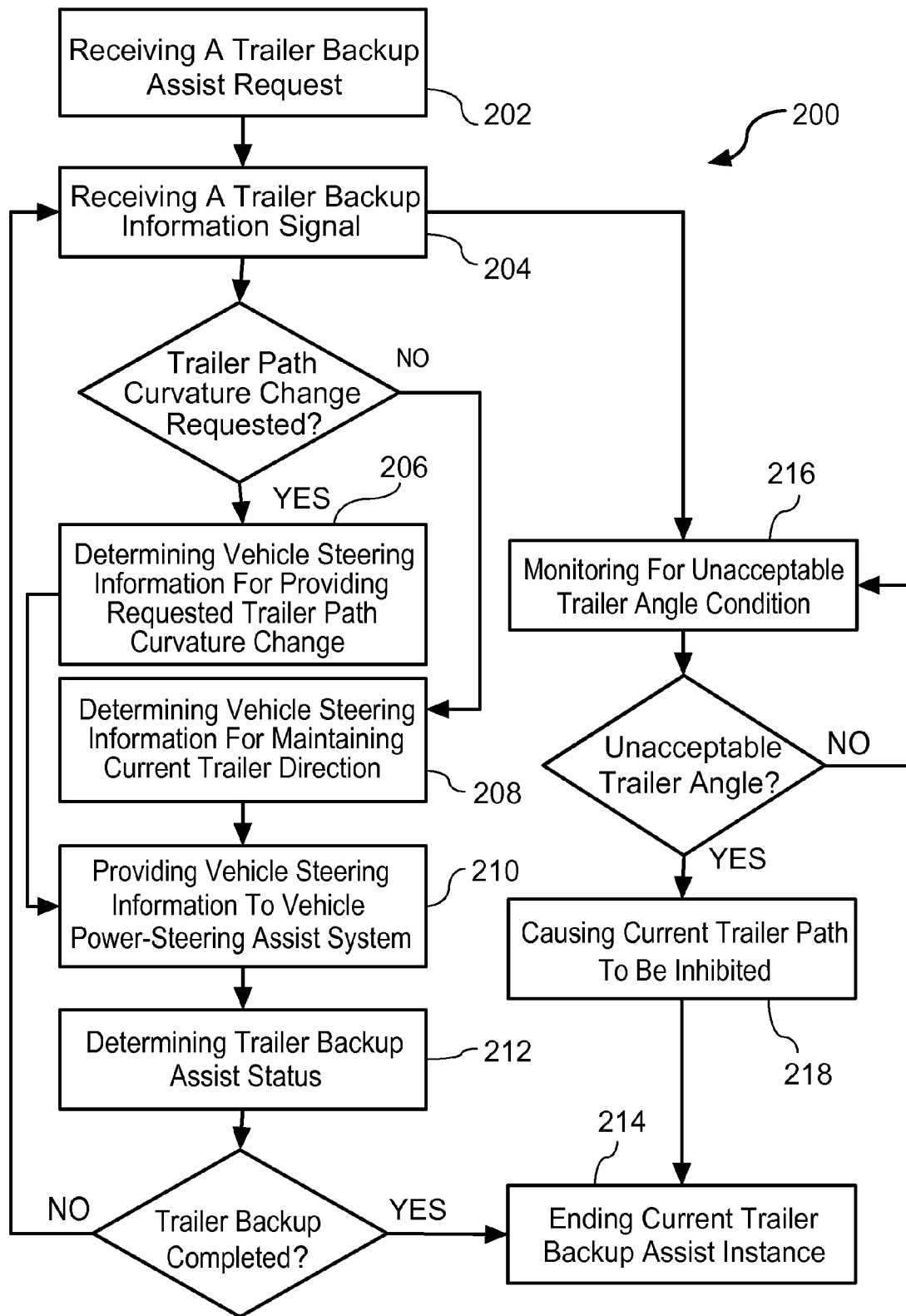


FIG. 2



**FIG. 3**

**FIG. 4**

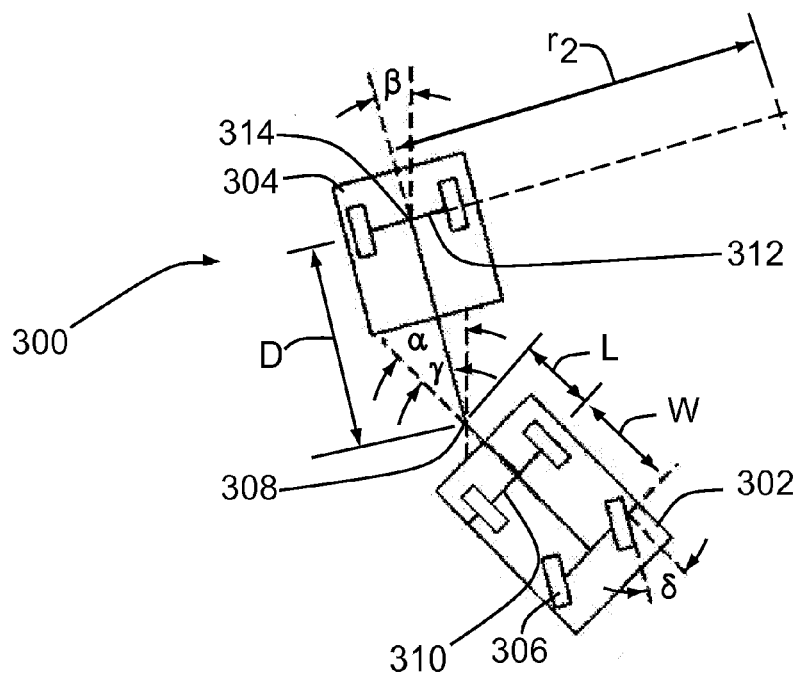


FIG. 5

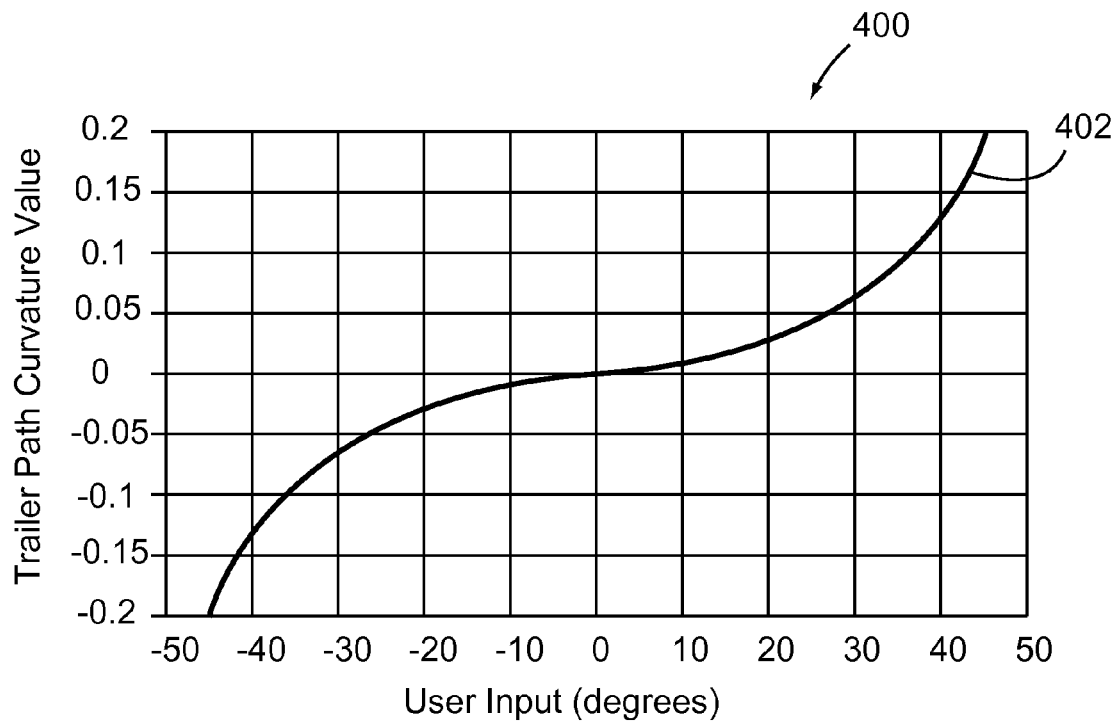


FIG. 6



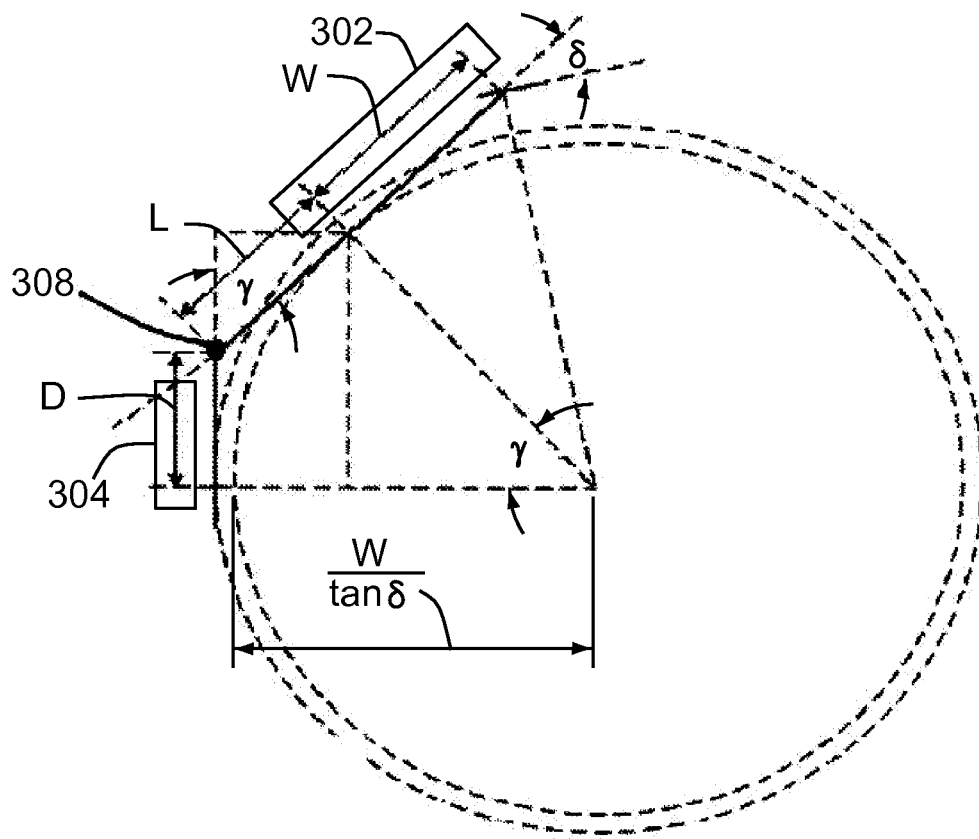
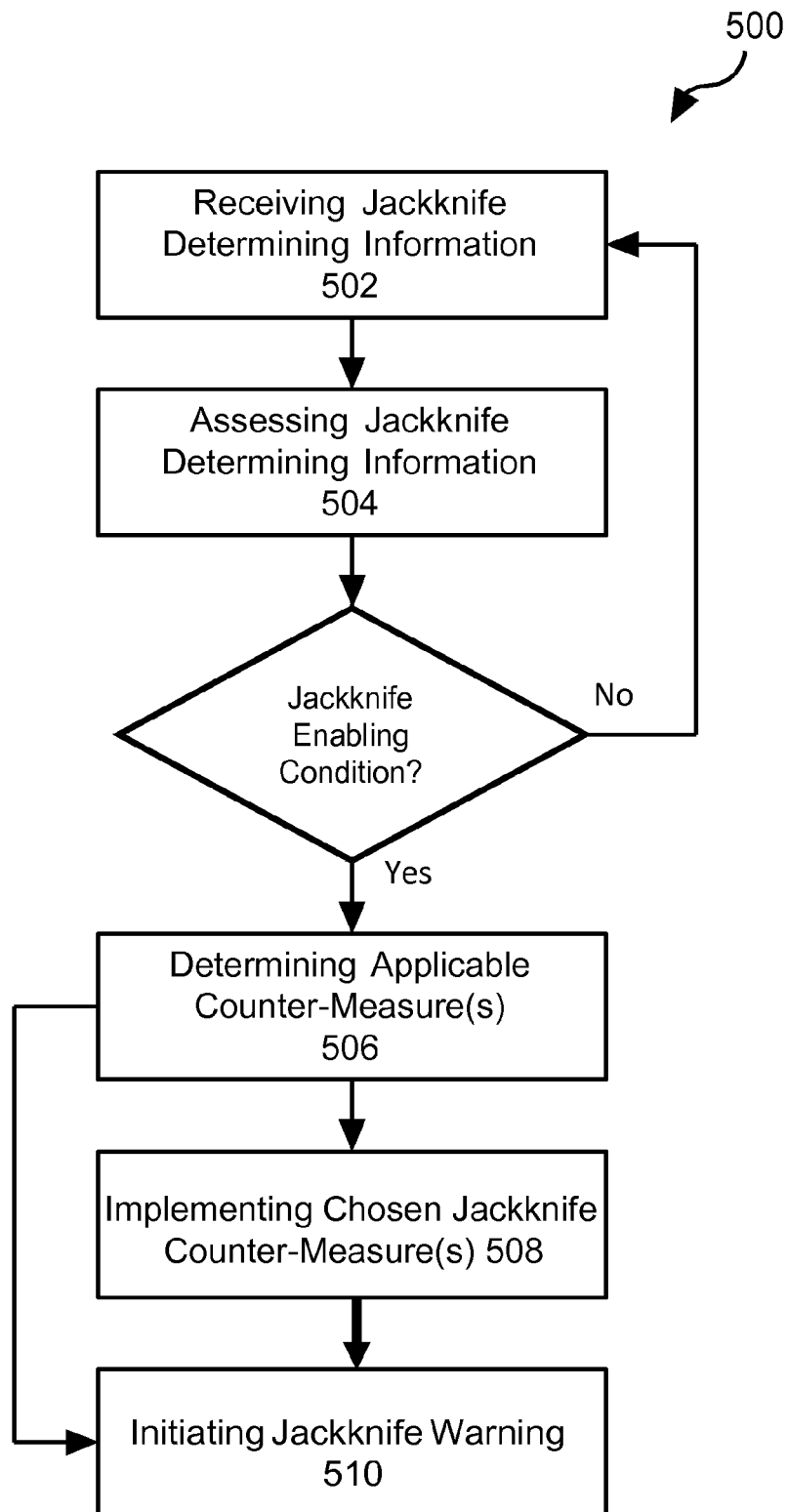


FIG. 7

**FIG. 8**

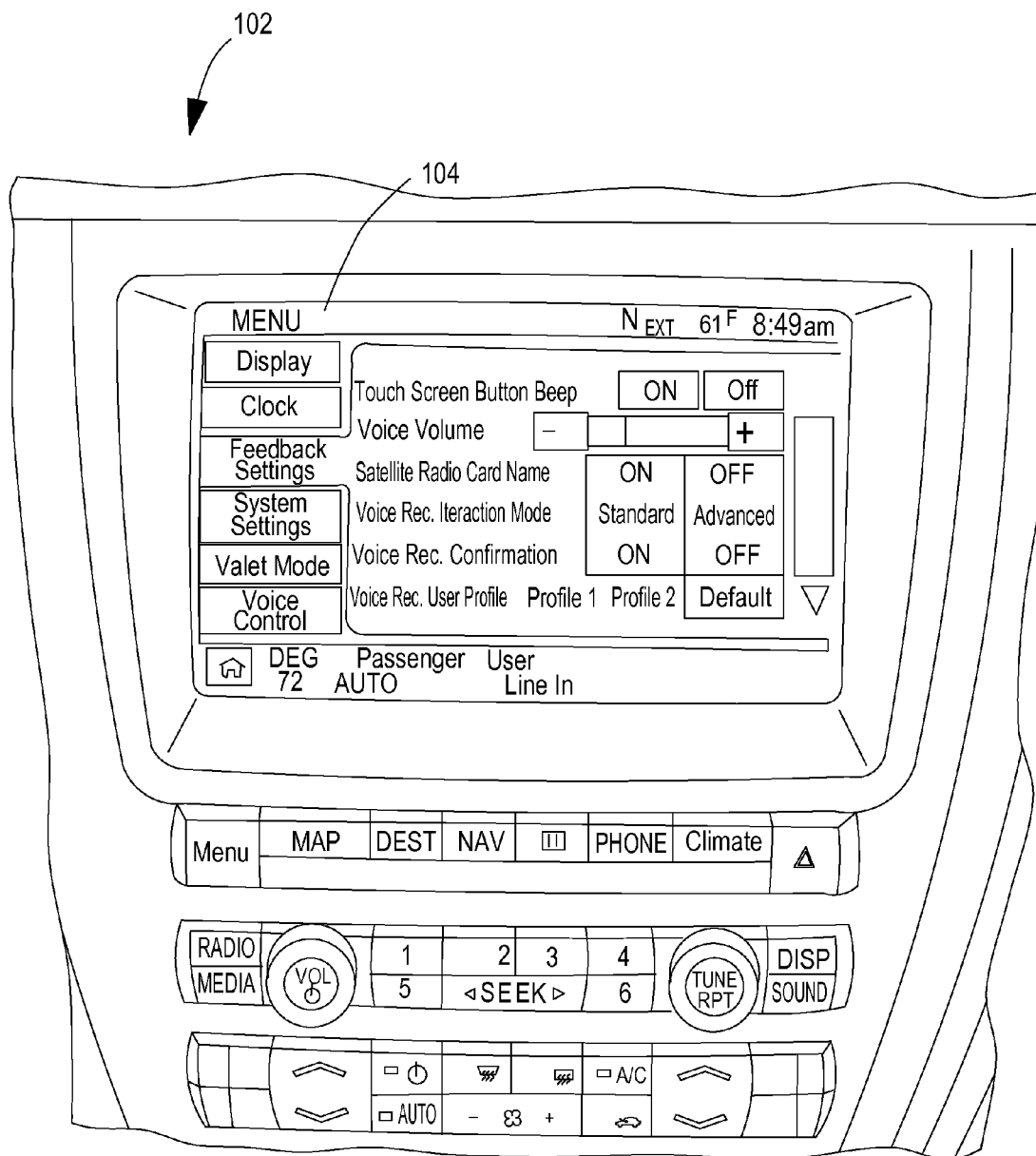


FIG. 9

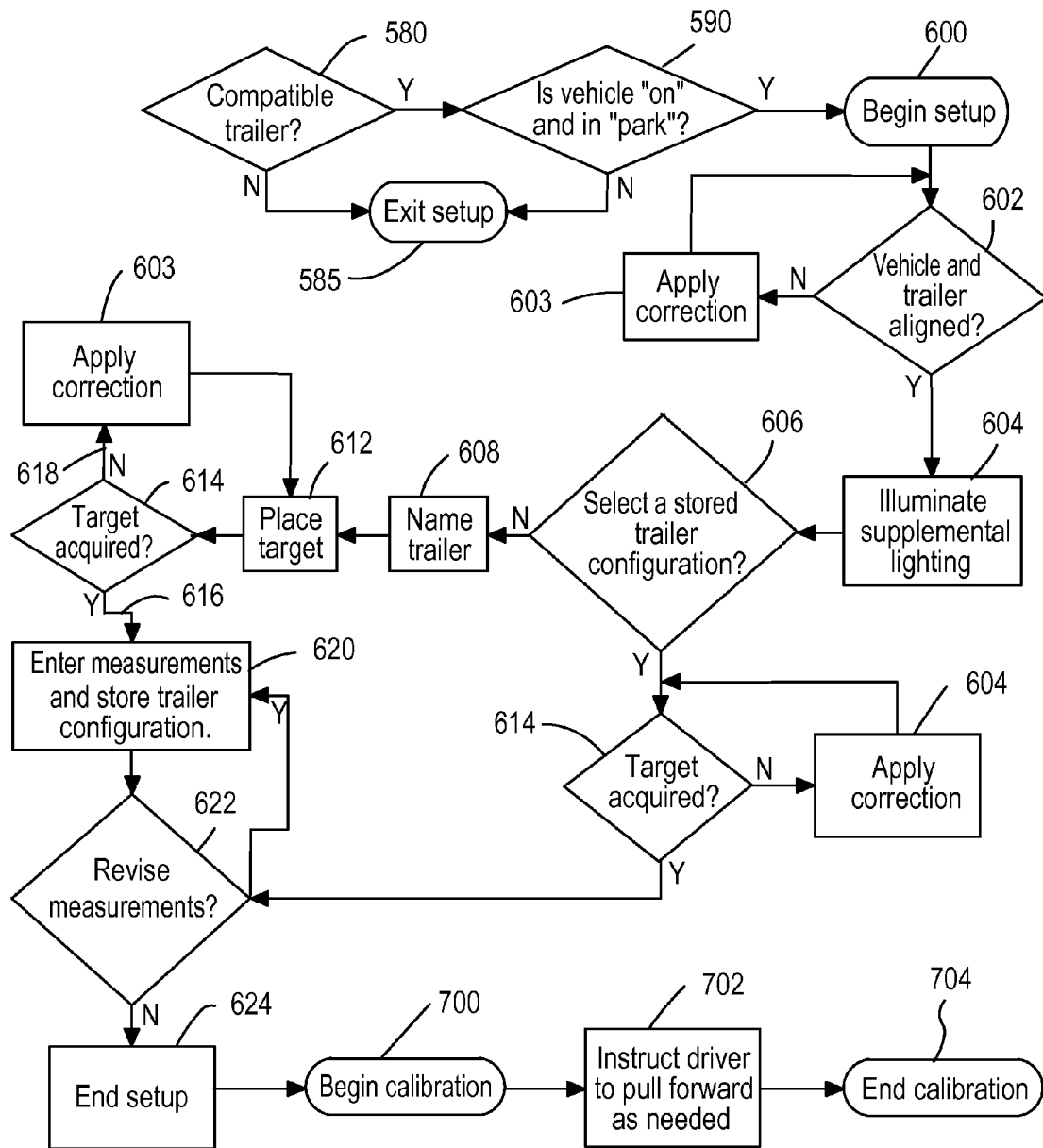
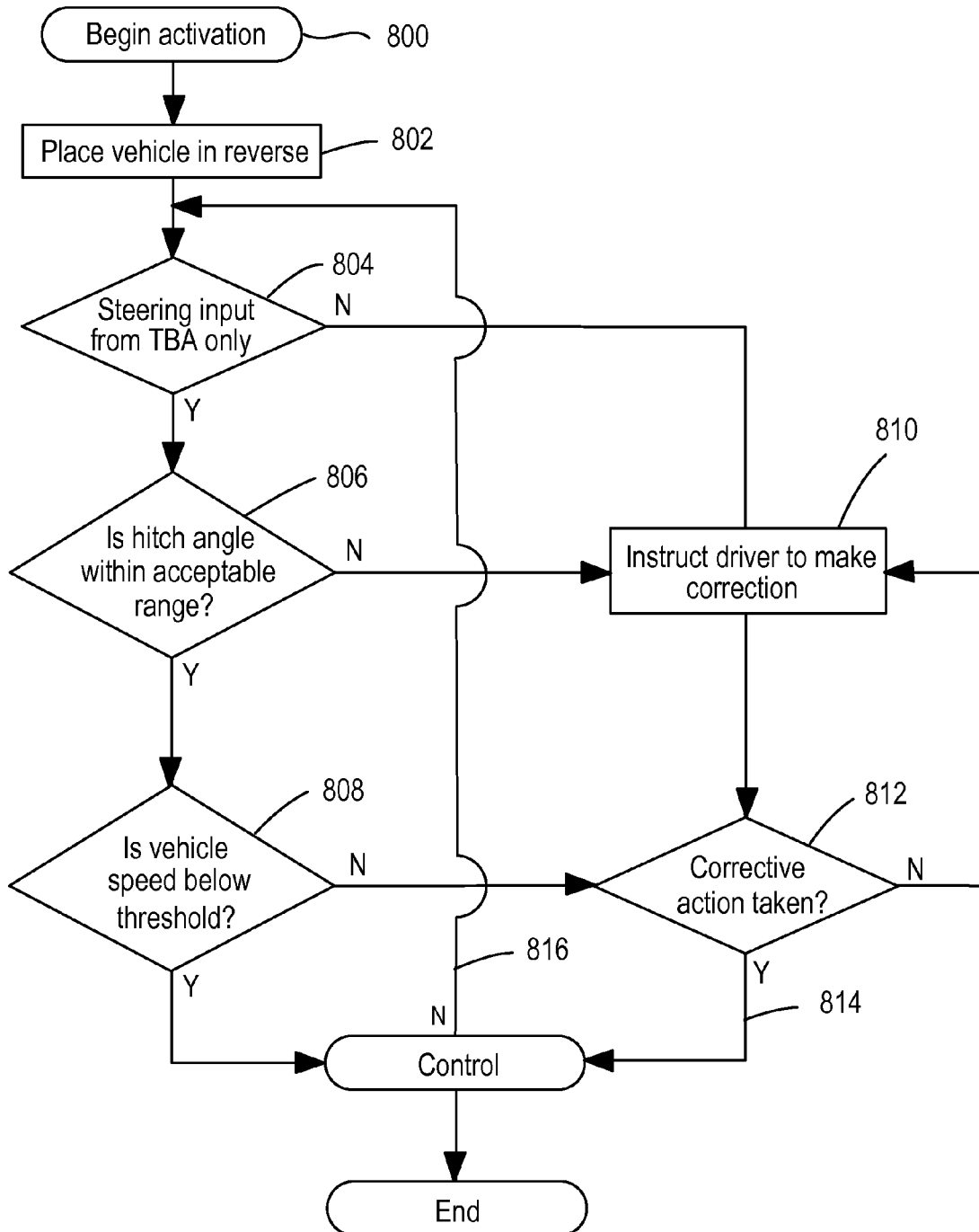
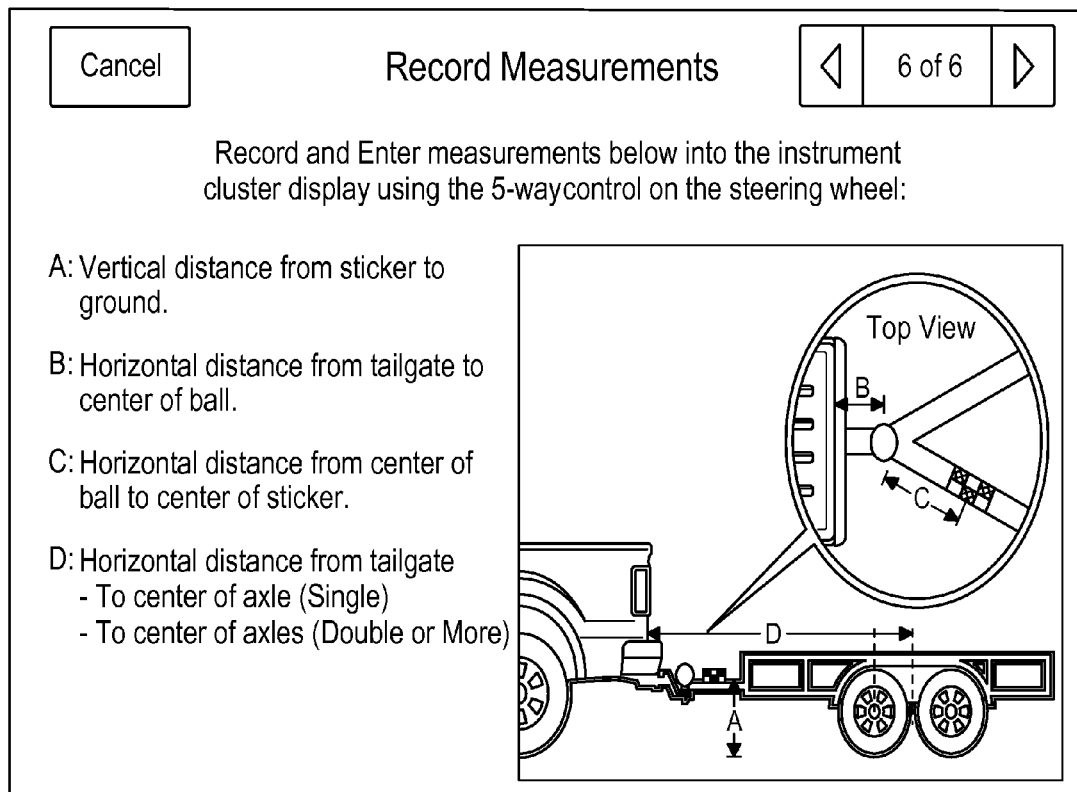
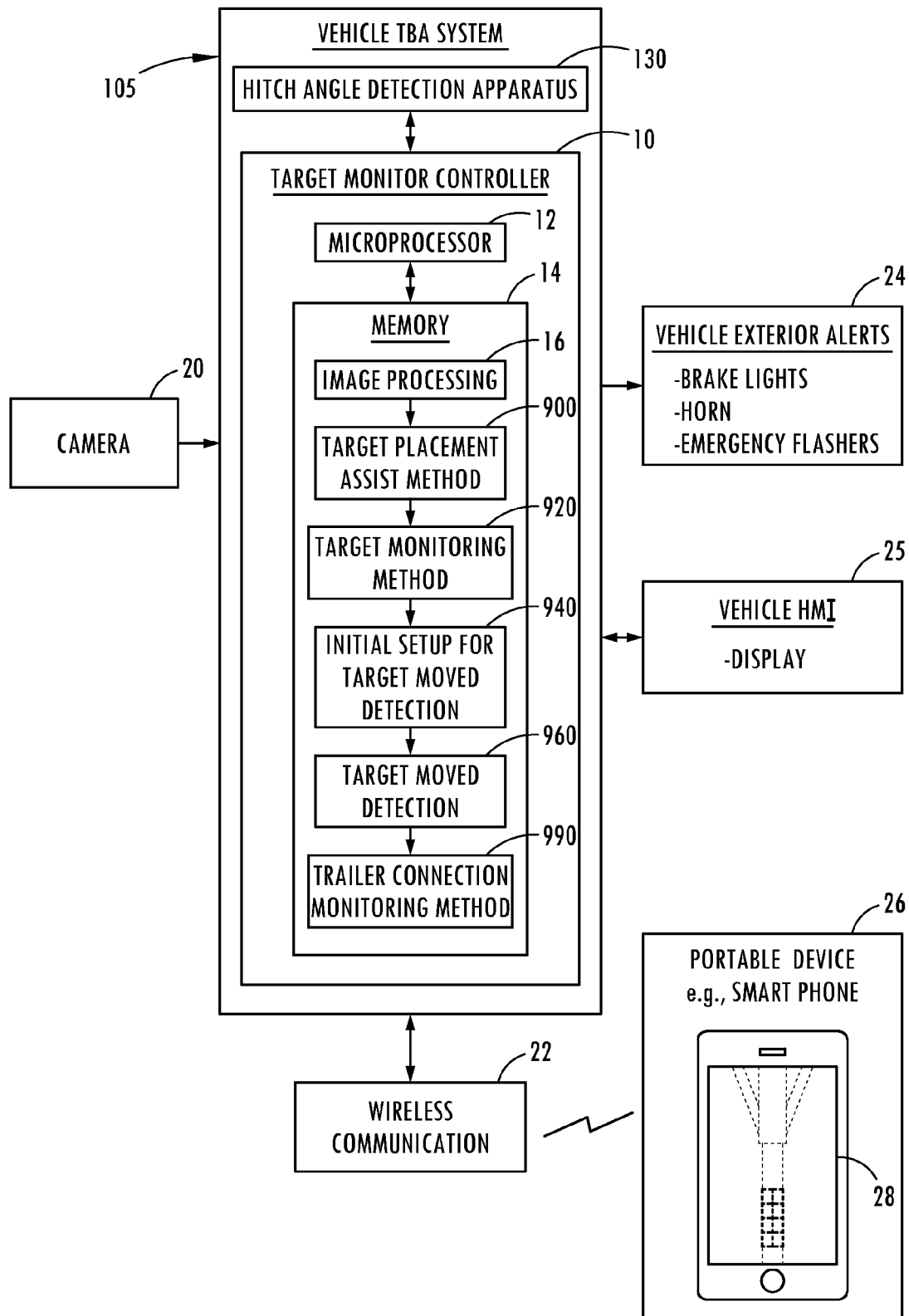


FIG. 10

**FIG. 11**

**FIG. 12**

**FIG. 13**

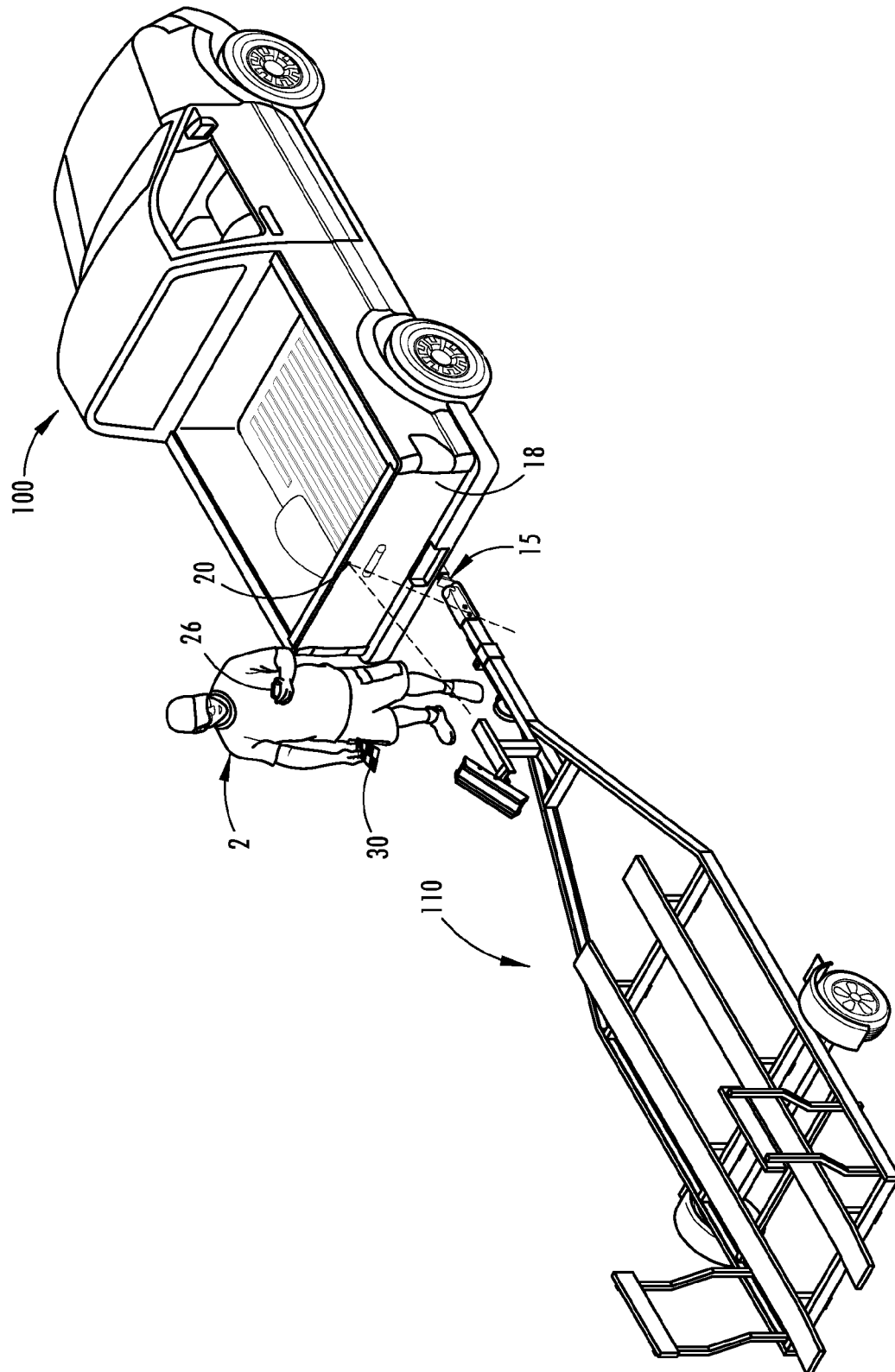


FIG. 14



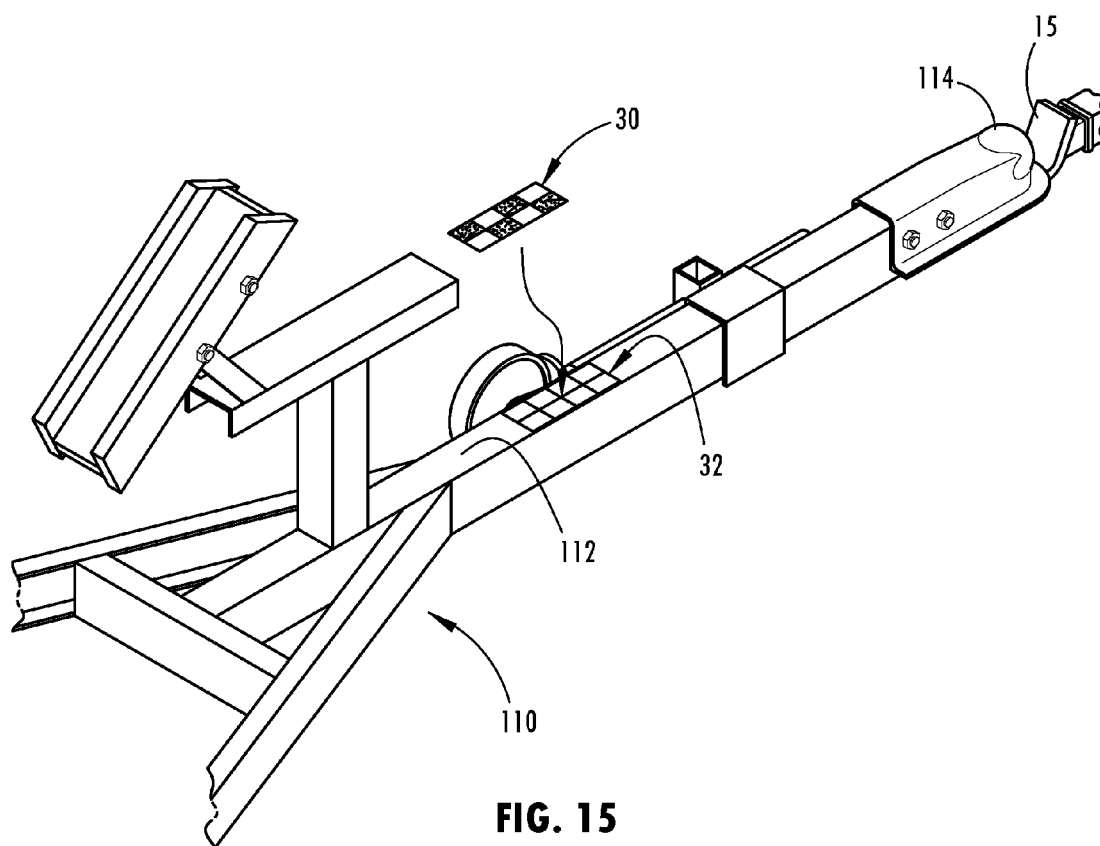


FIG. 15

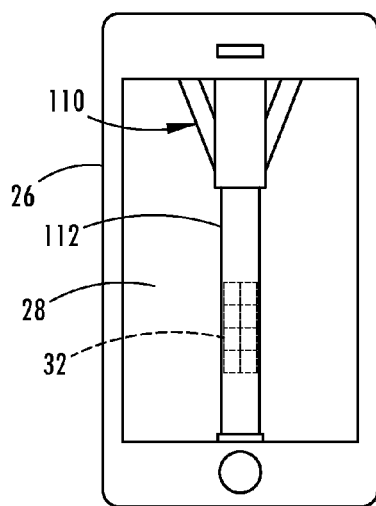
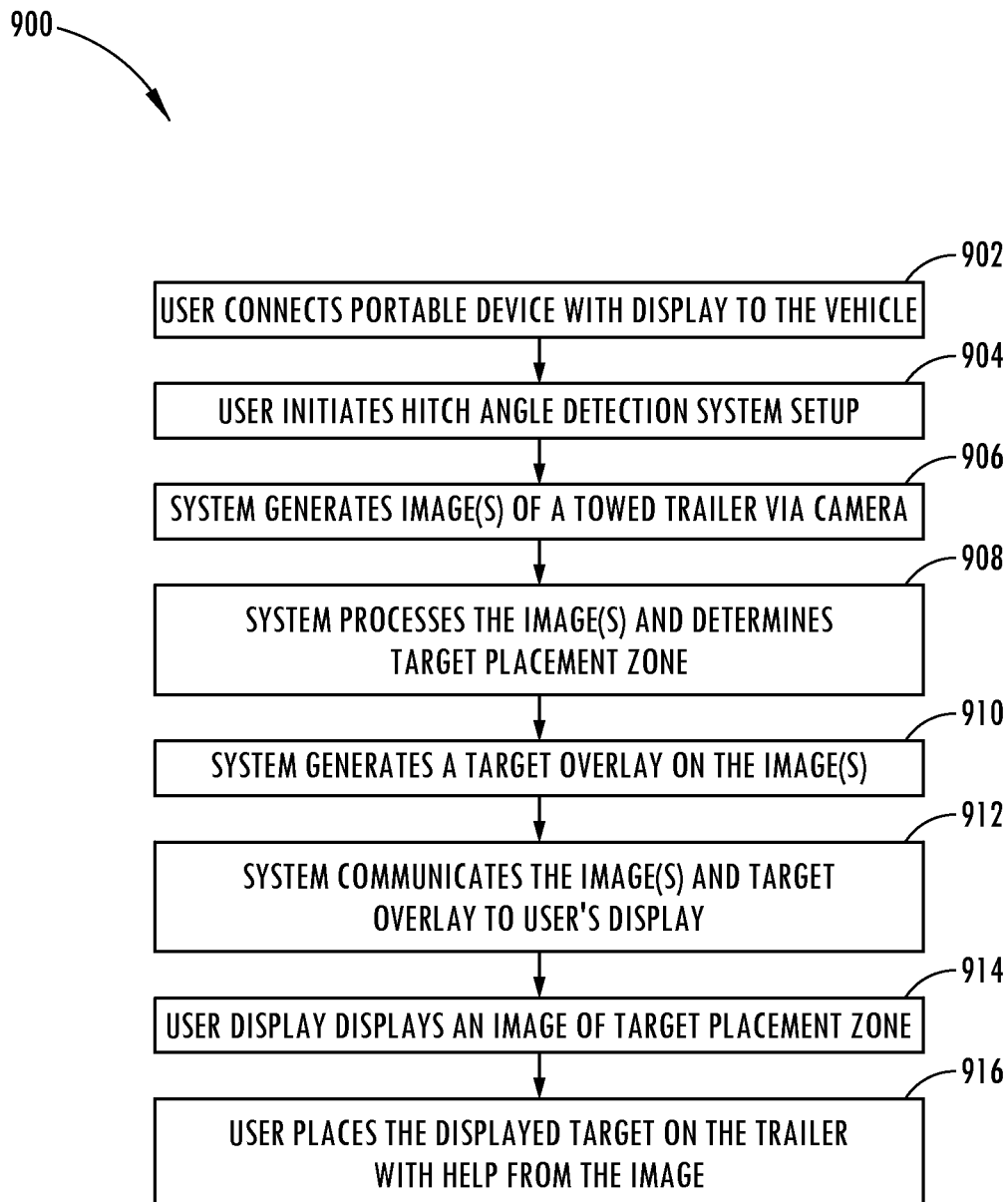
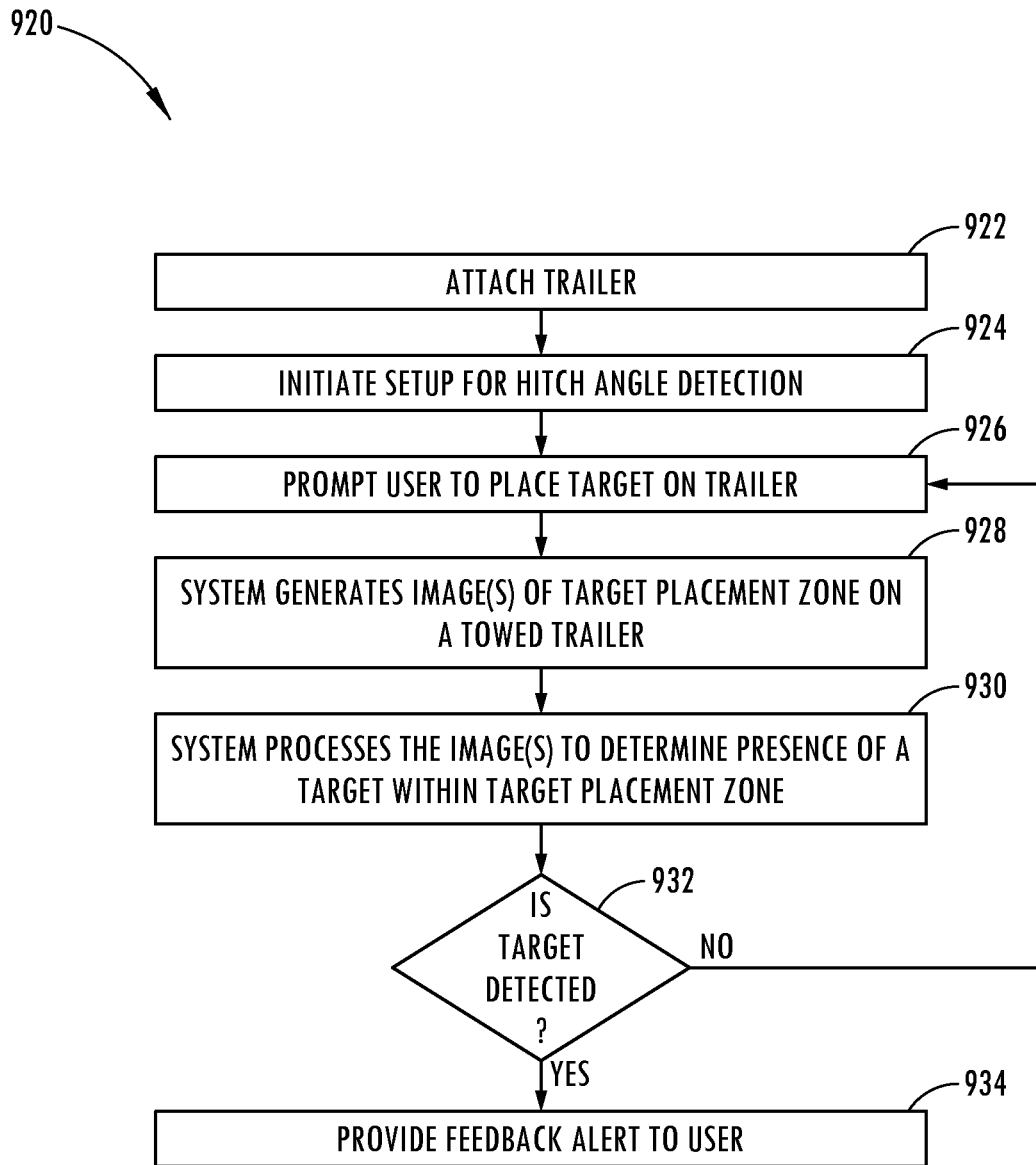
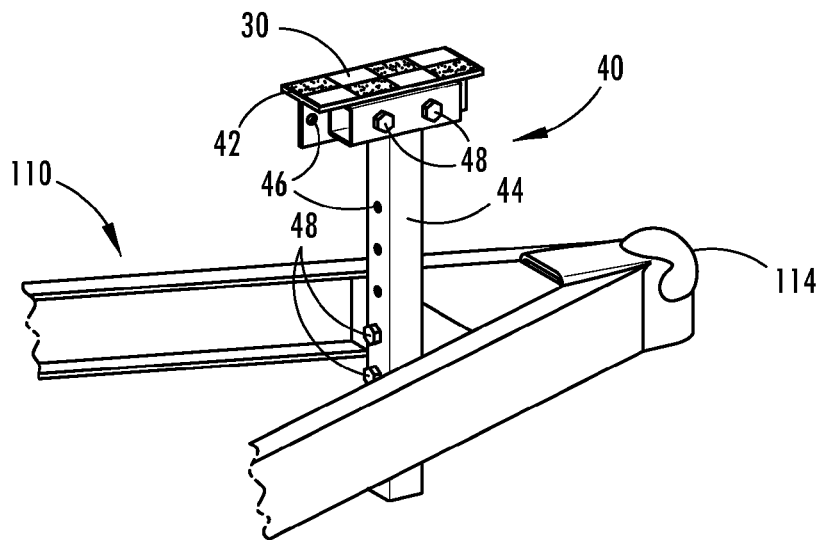


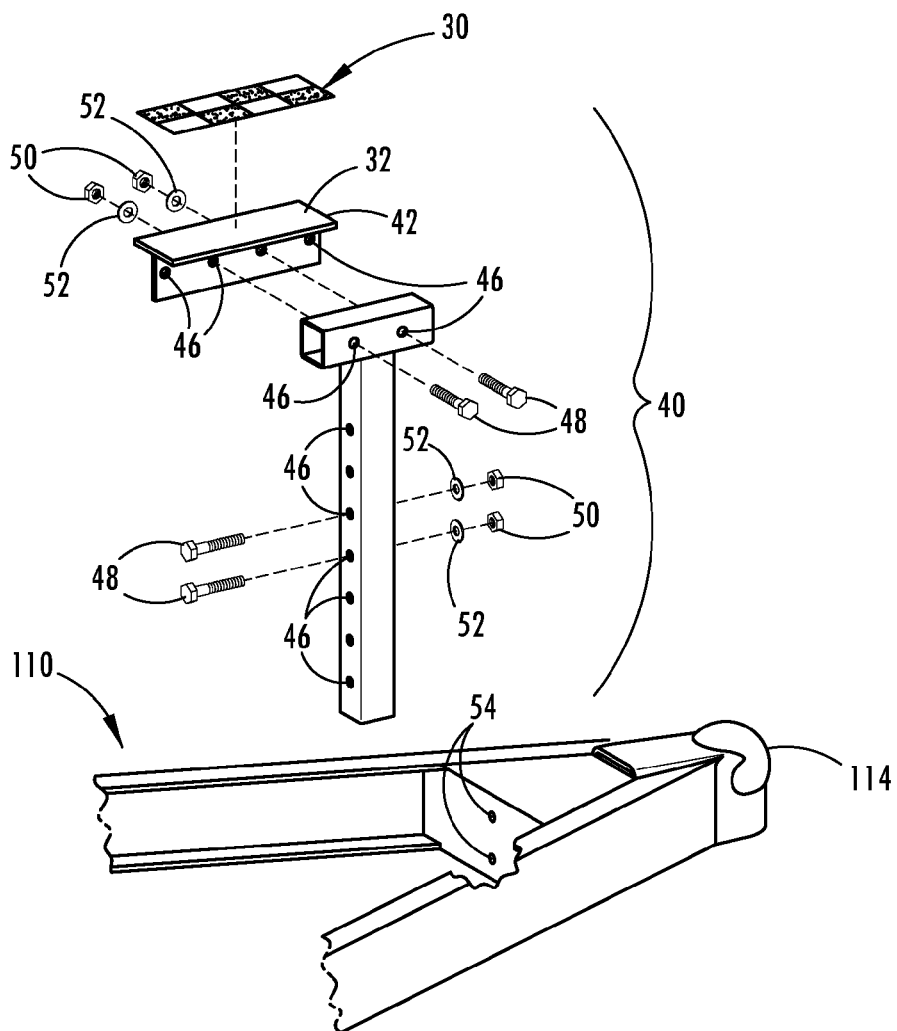
FIG. 16

**FIG. 17**

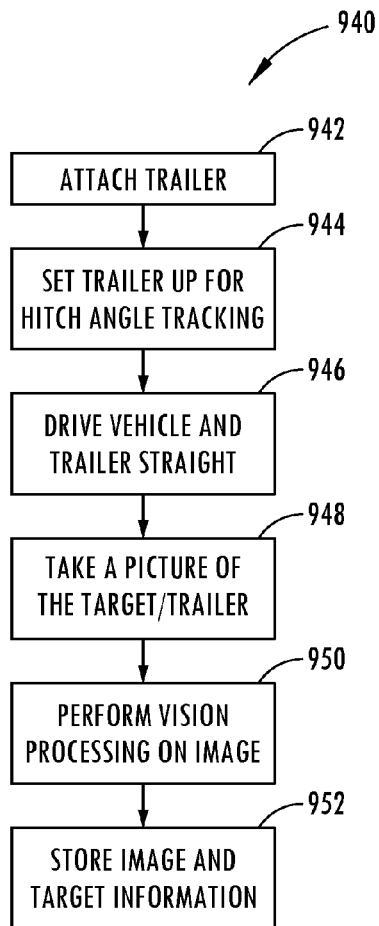
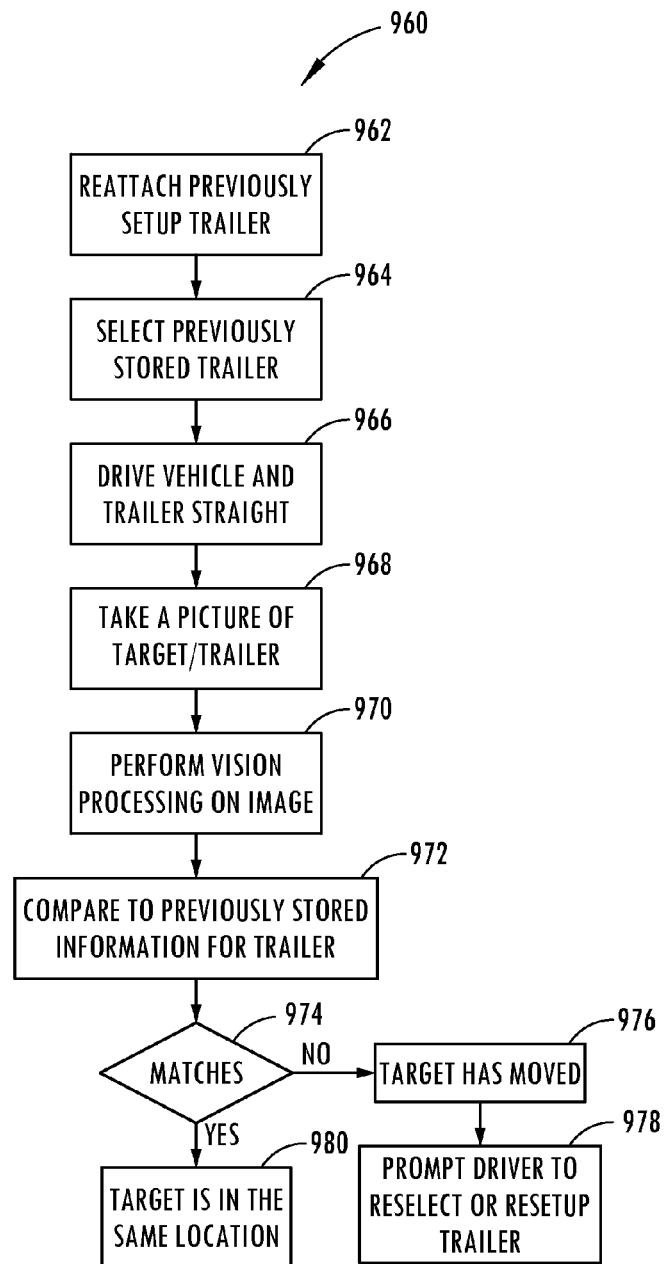
**FIG. 18**

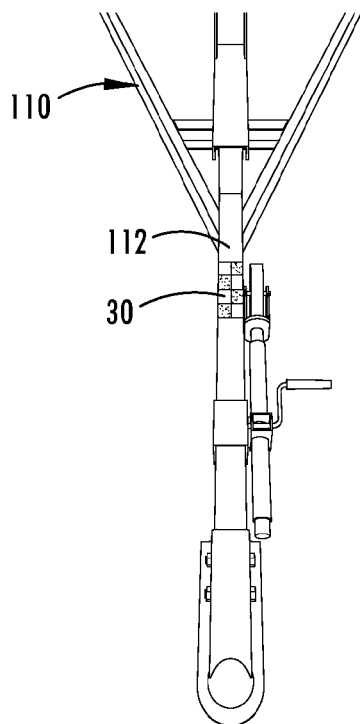


**FIG. 19**

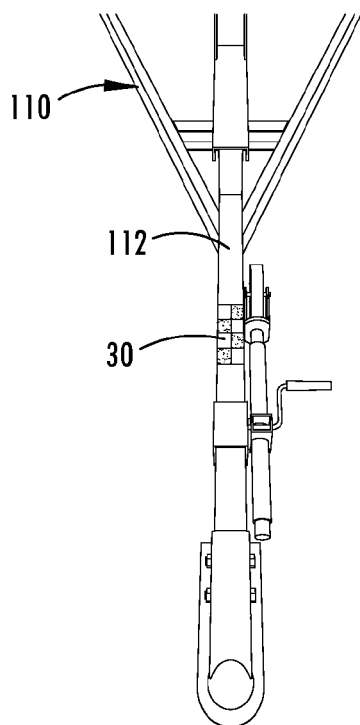


**FIG. 20**

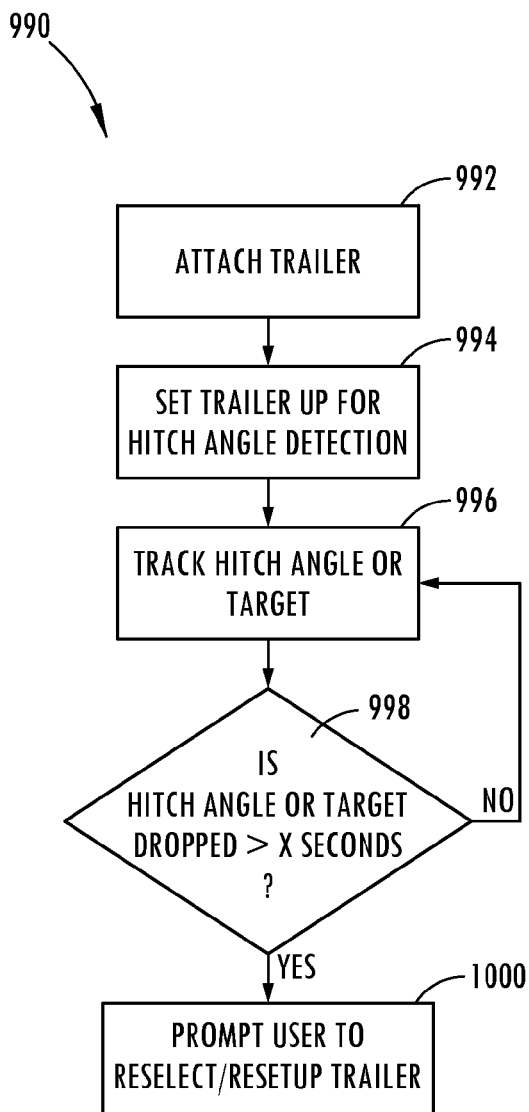
**FIG. 21****FIG. 22**



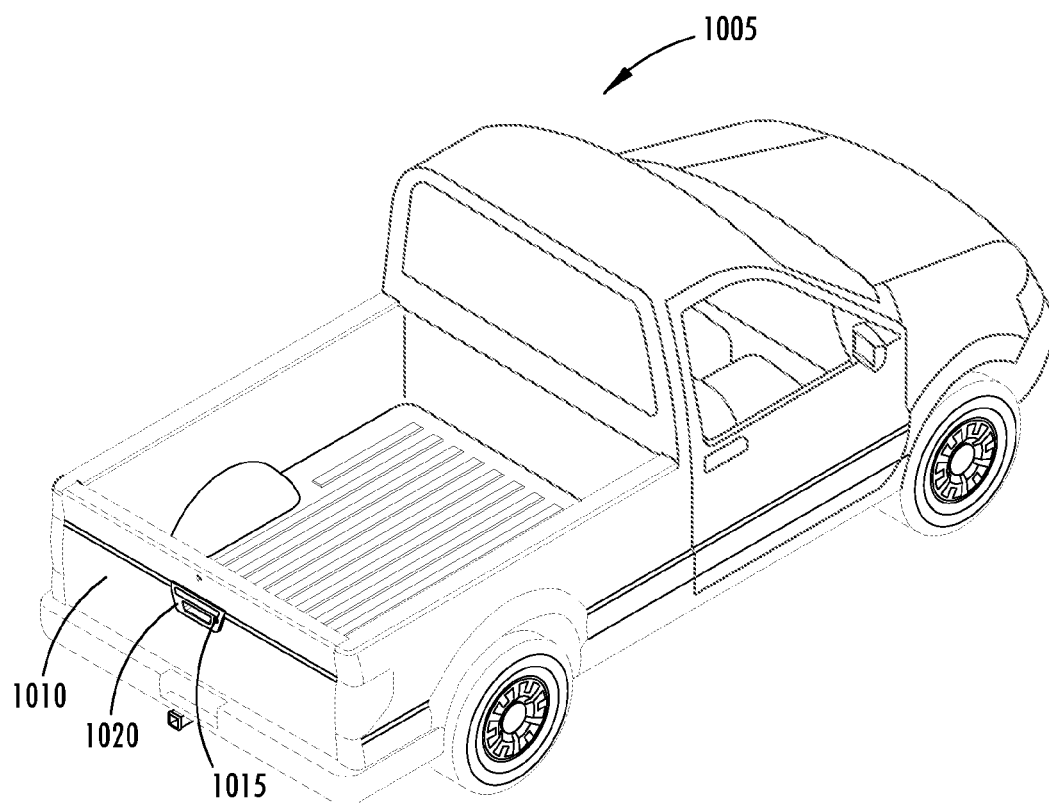
**FIG. 23A**



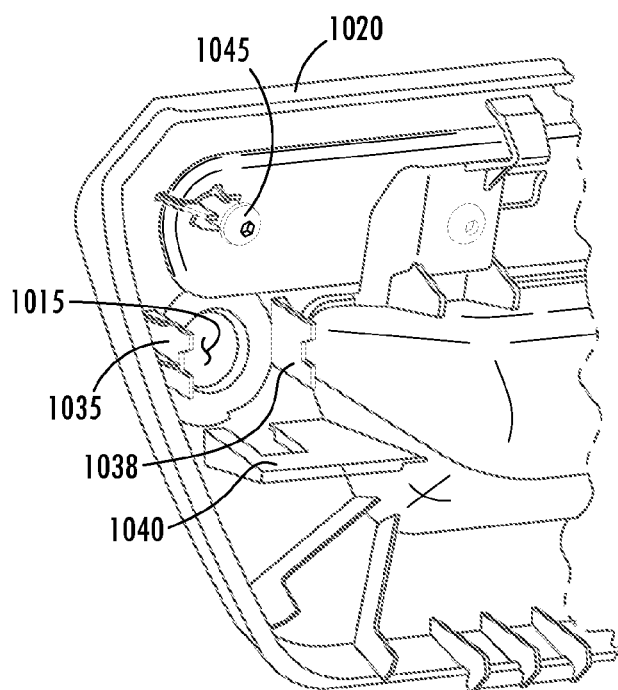
**FIG. 23B**



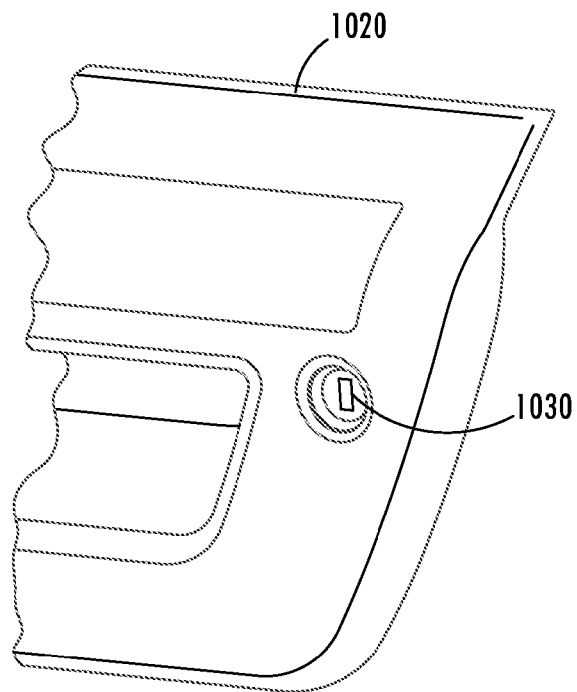
**FIG. 24**



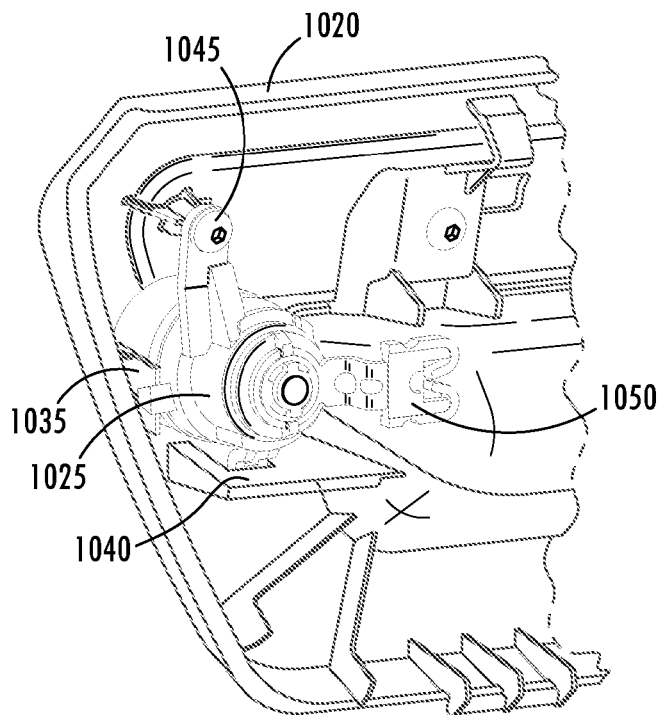
**FIG. 25A**



**FIG. 25B**

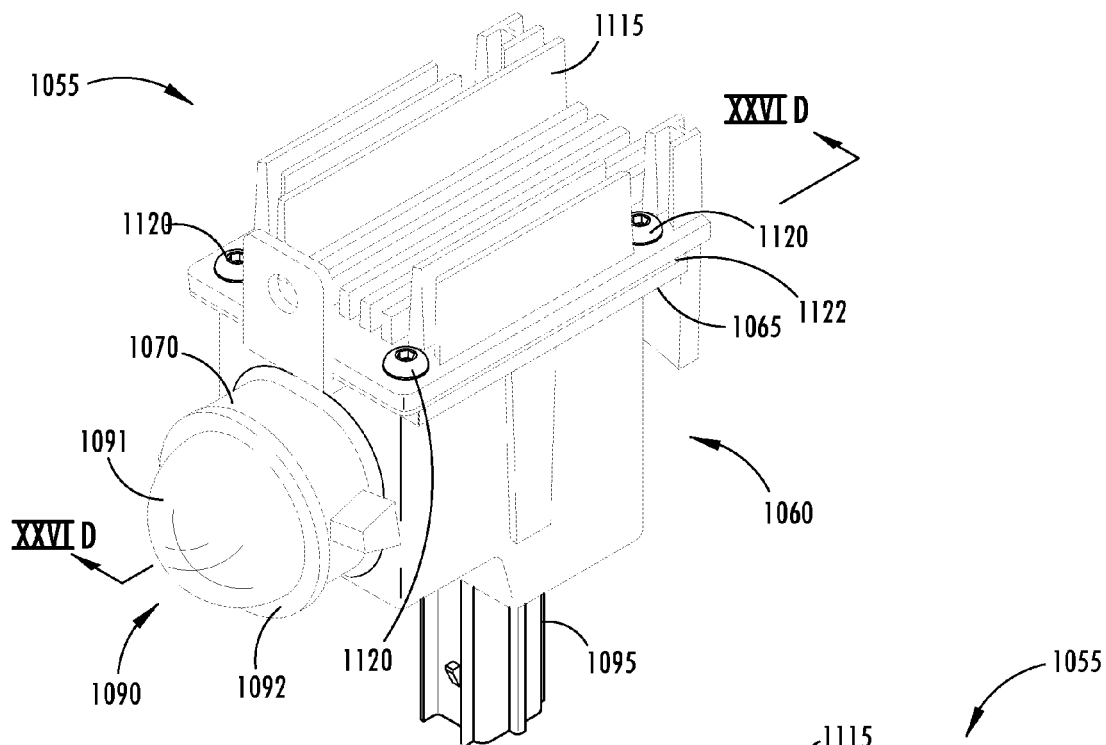


**FIG. 25C**

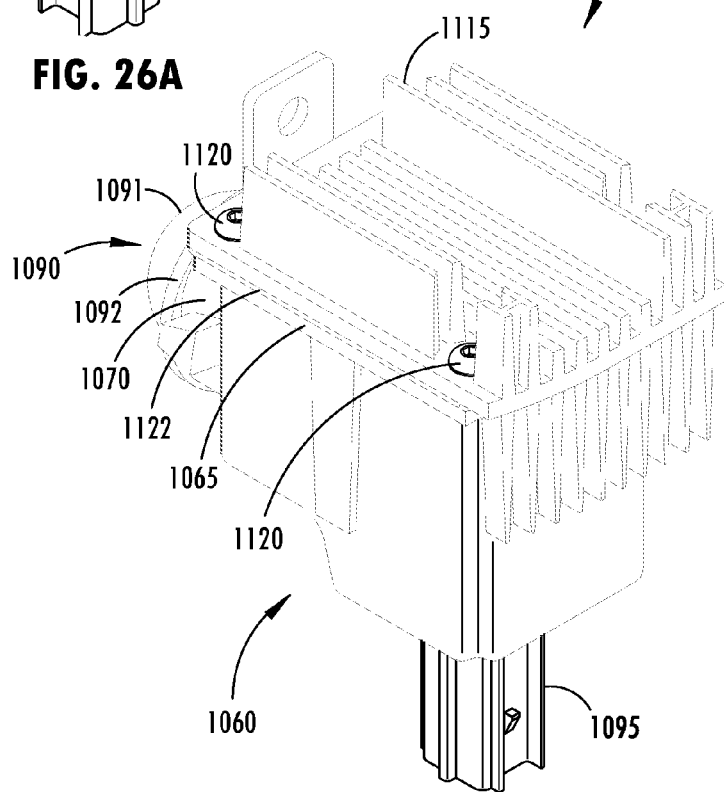


**FIG. 25D**





**FIG. 26A**



**FIG. 26B**

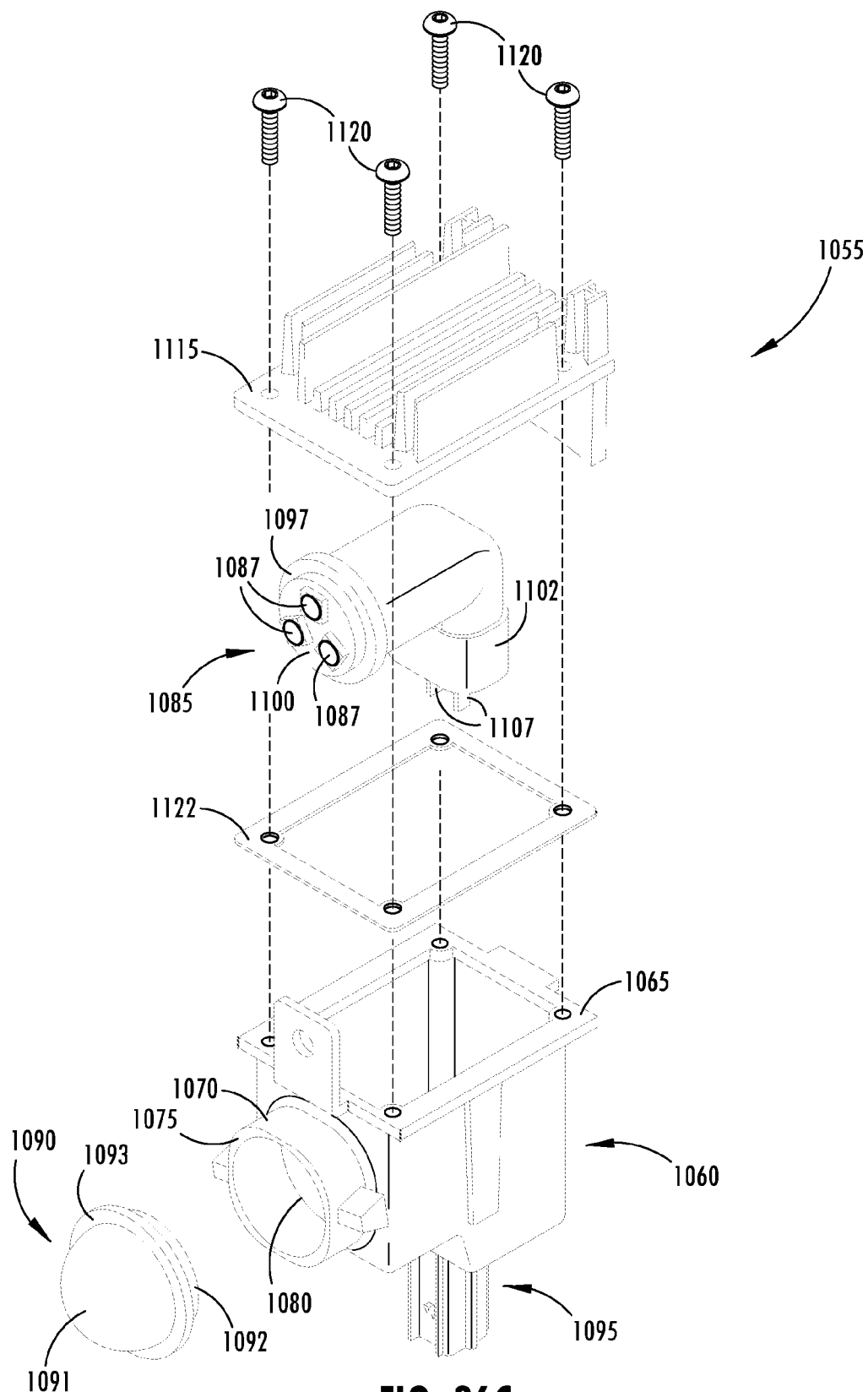


FIG. 26C

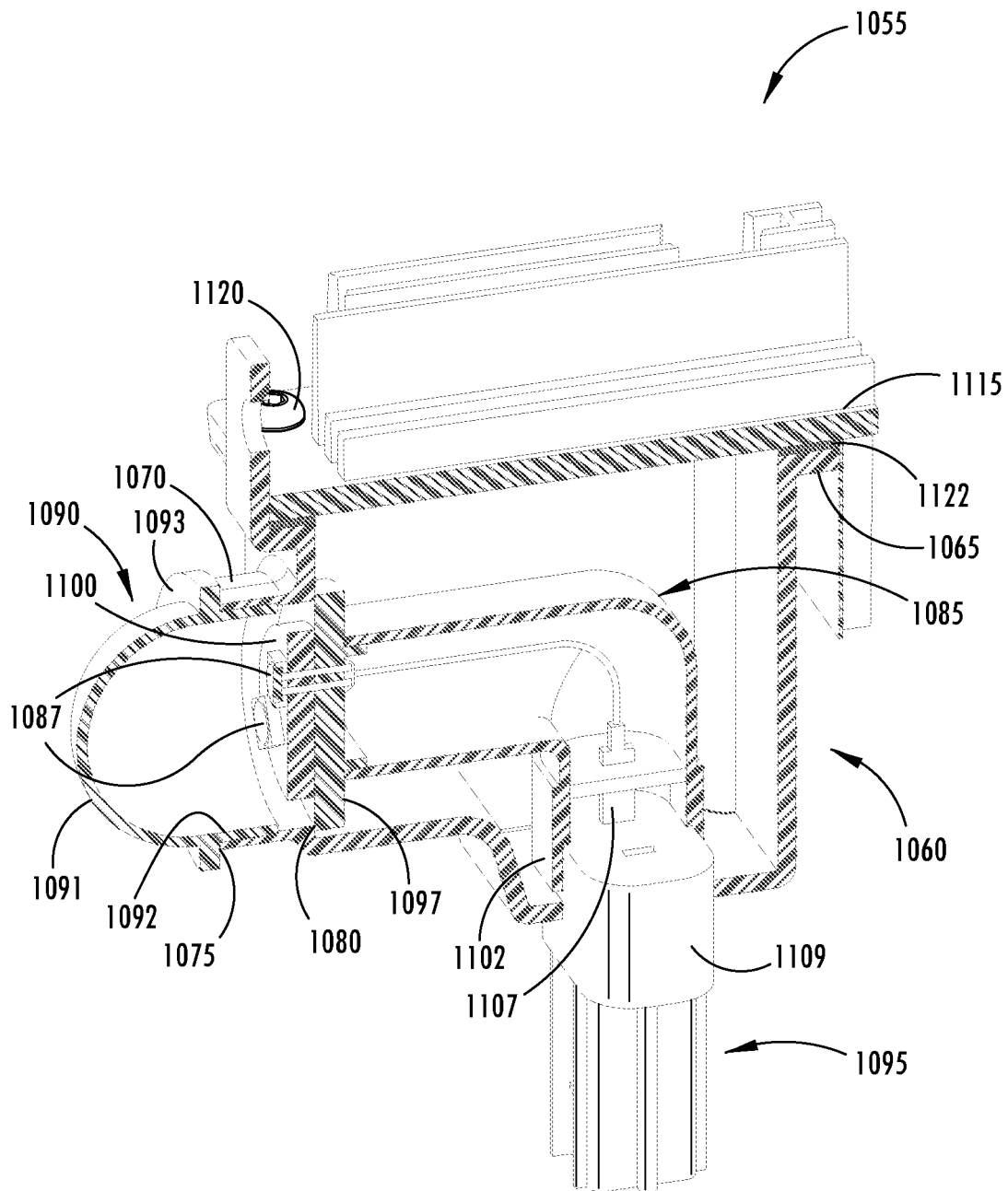
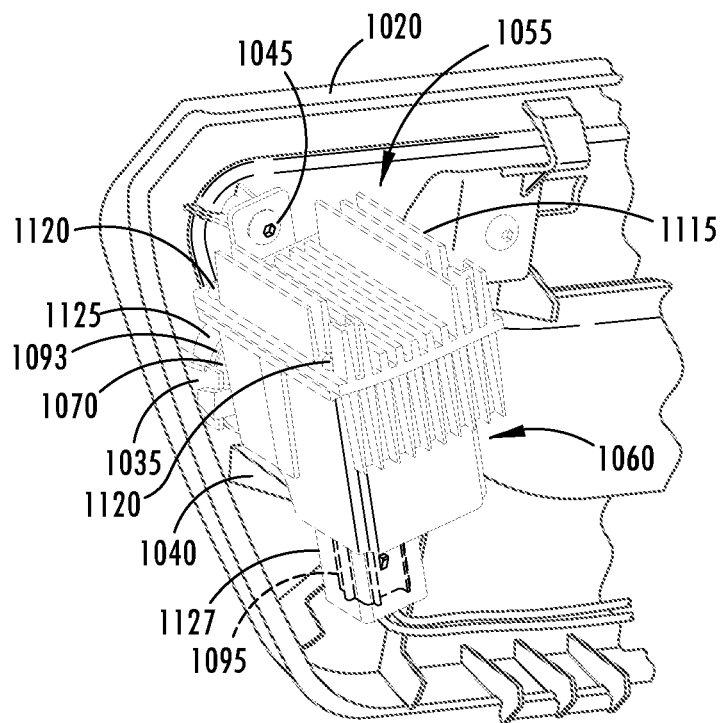
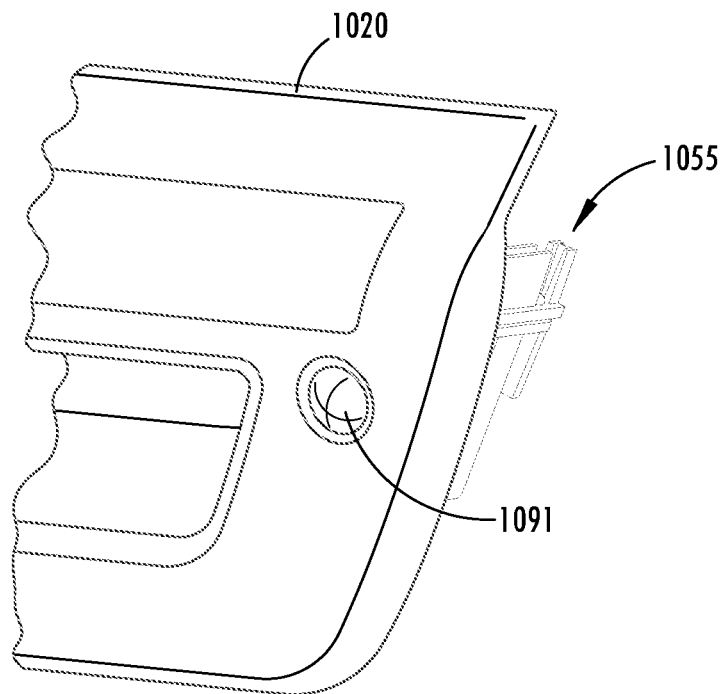


FIG. 26D



**FIG. 27A**



**FIG. 27B**

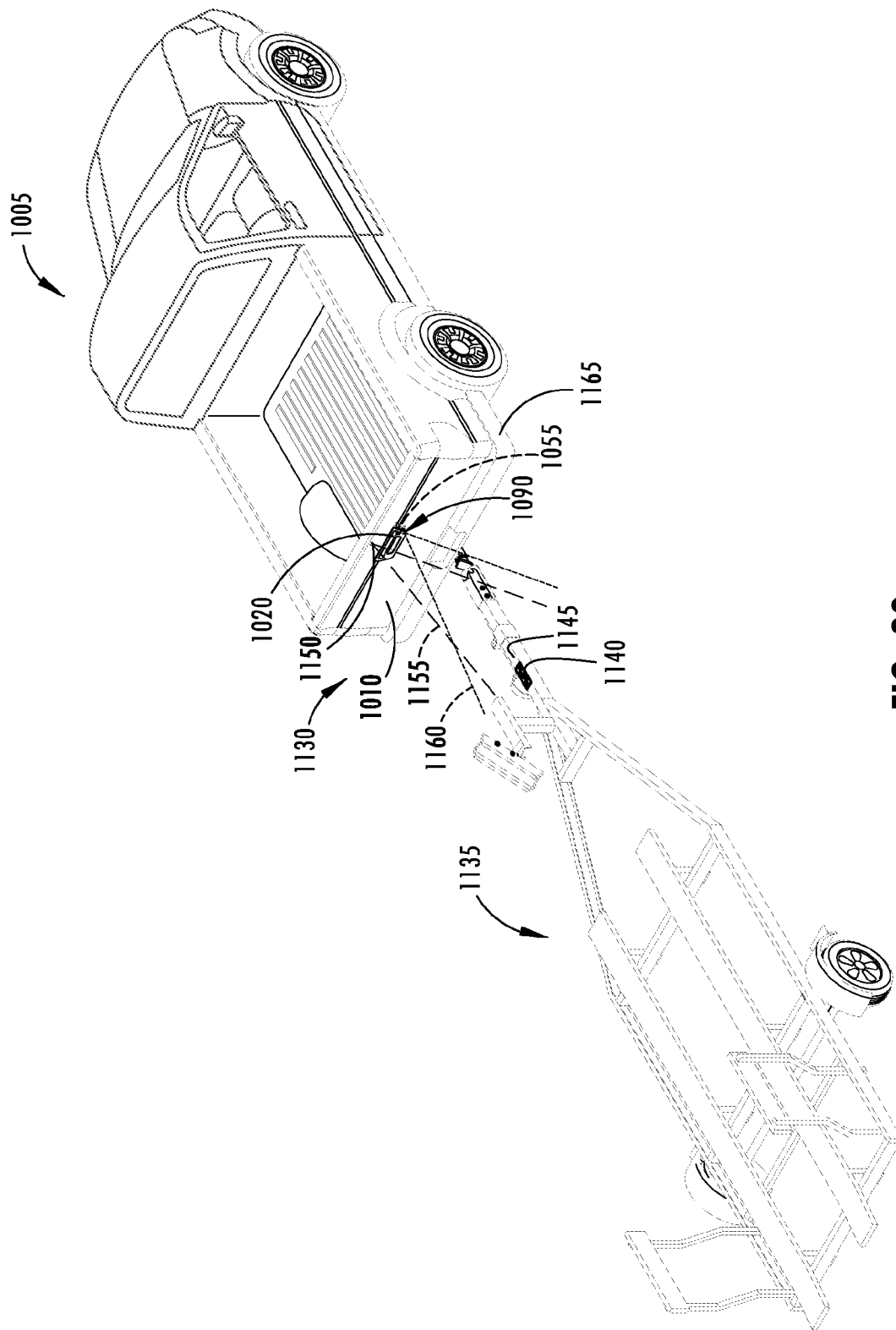
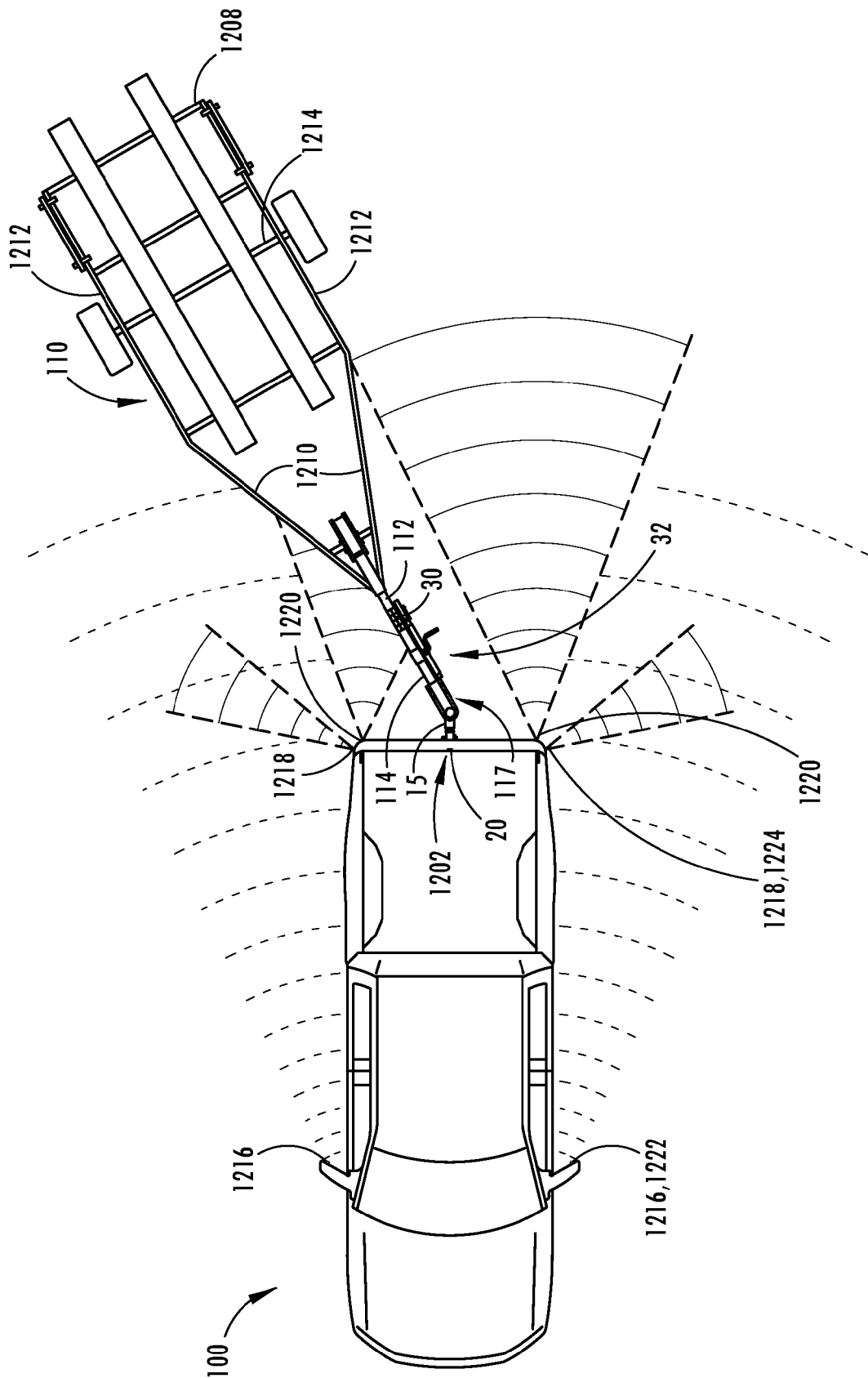


FIG. 28



**FIG. 29**

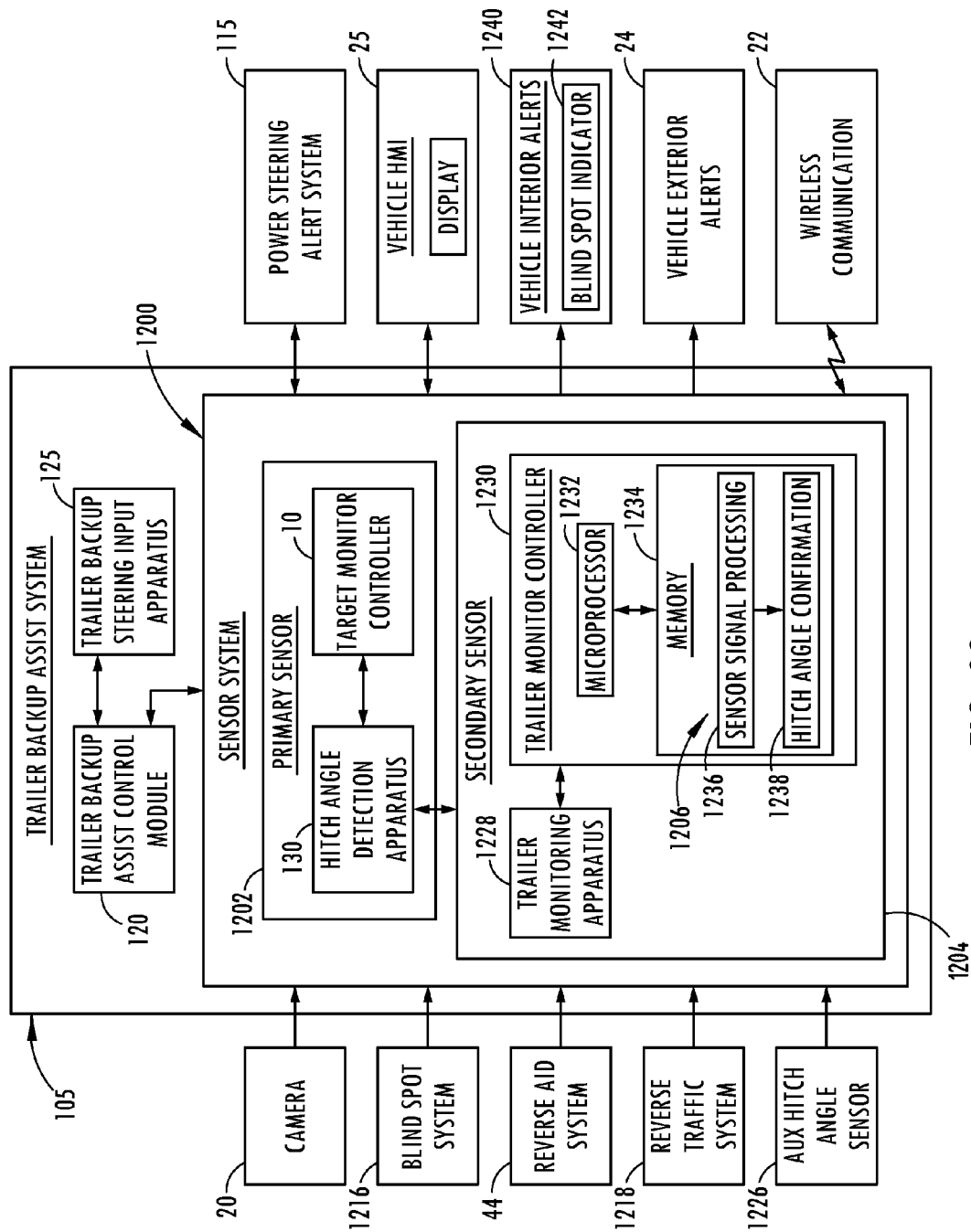
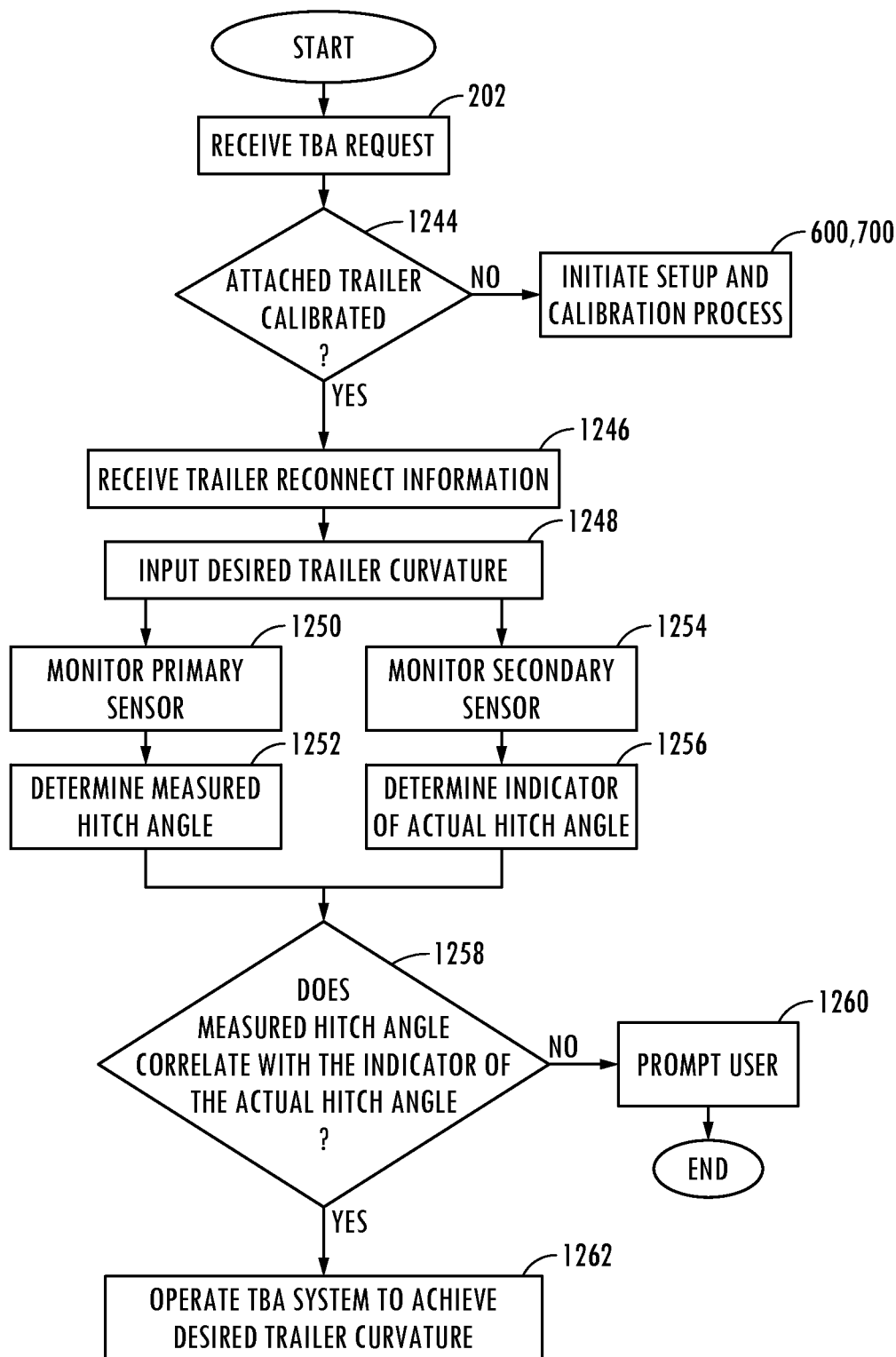


FIG. 30

**FIG. 31**



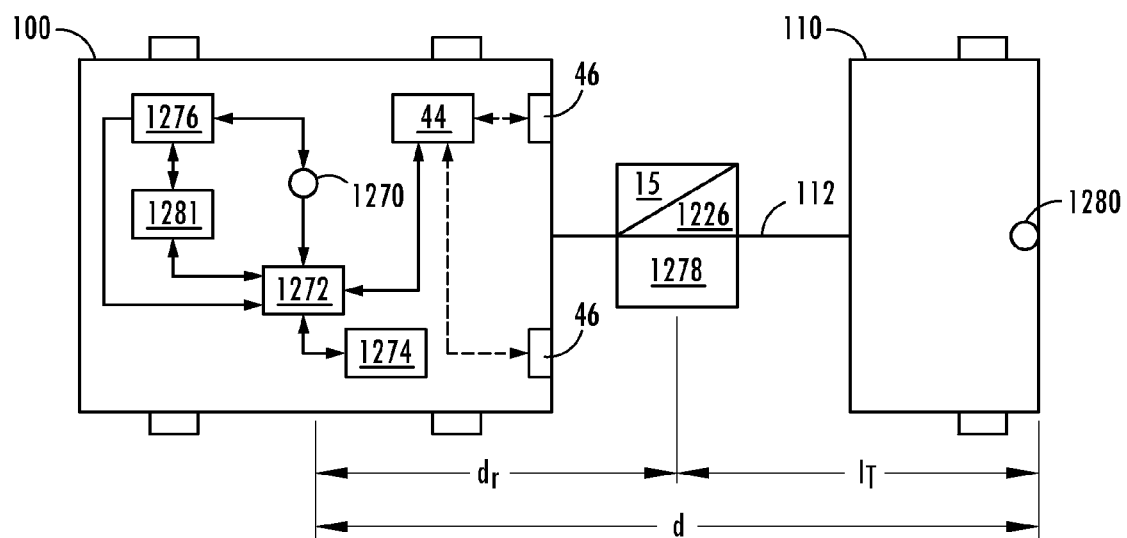


FIG. 32

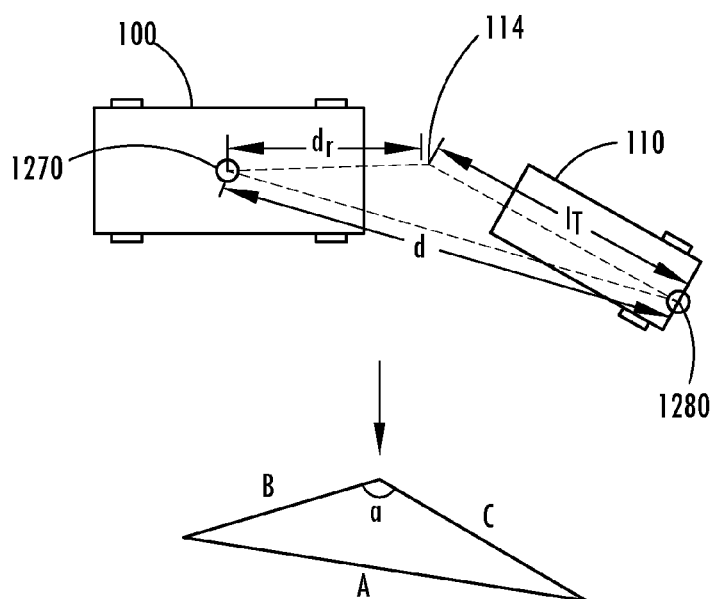
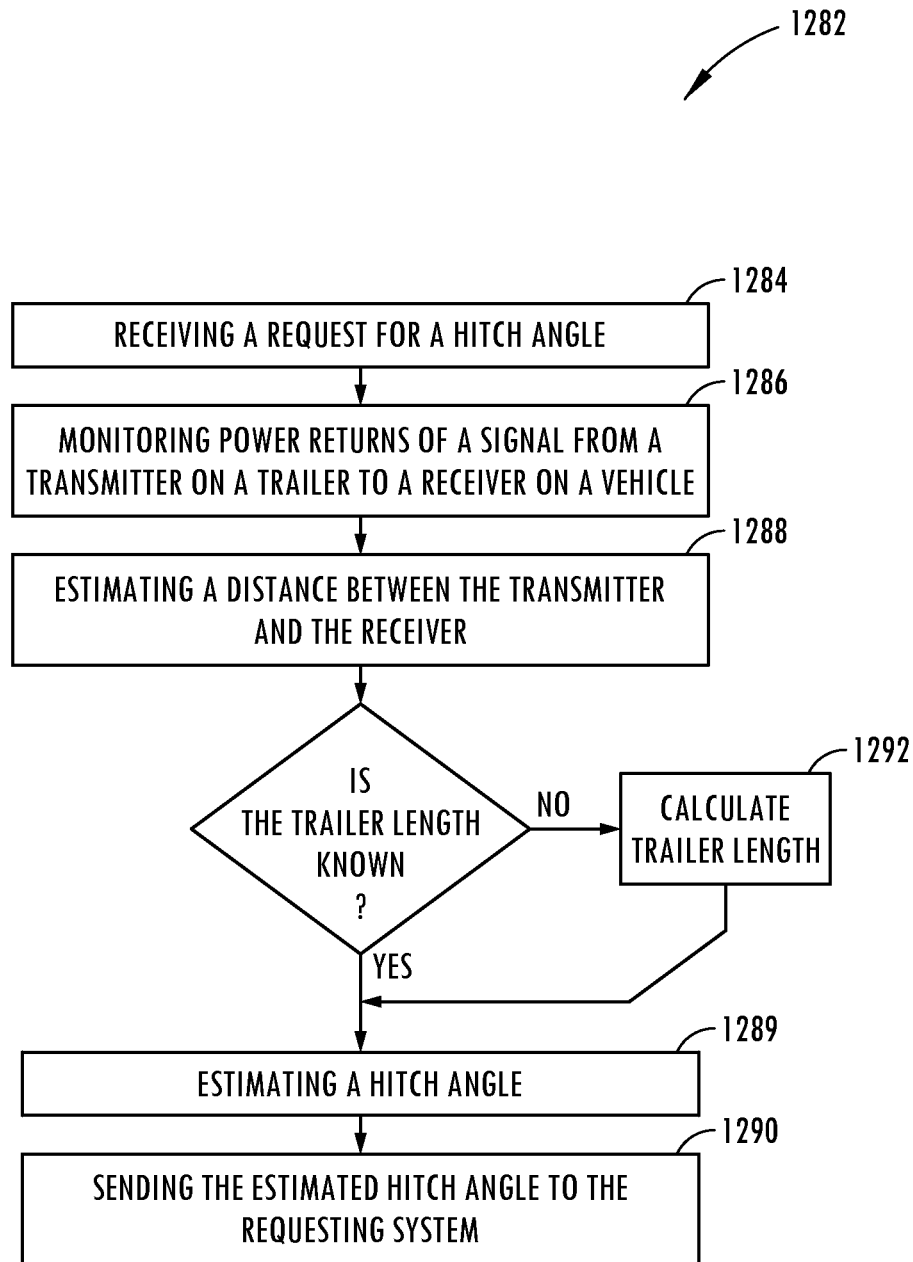


FIG. 33

**FIG. 34**

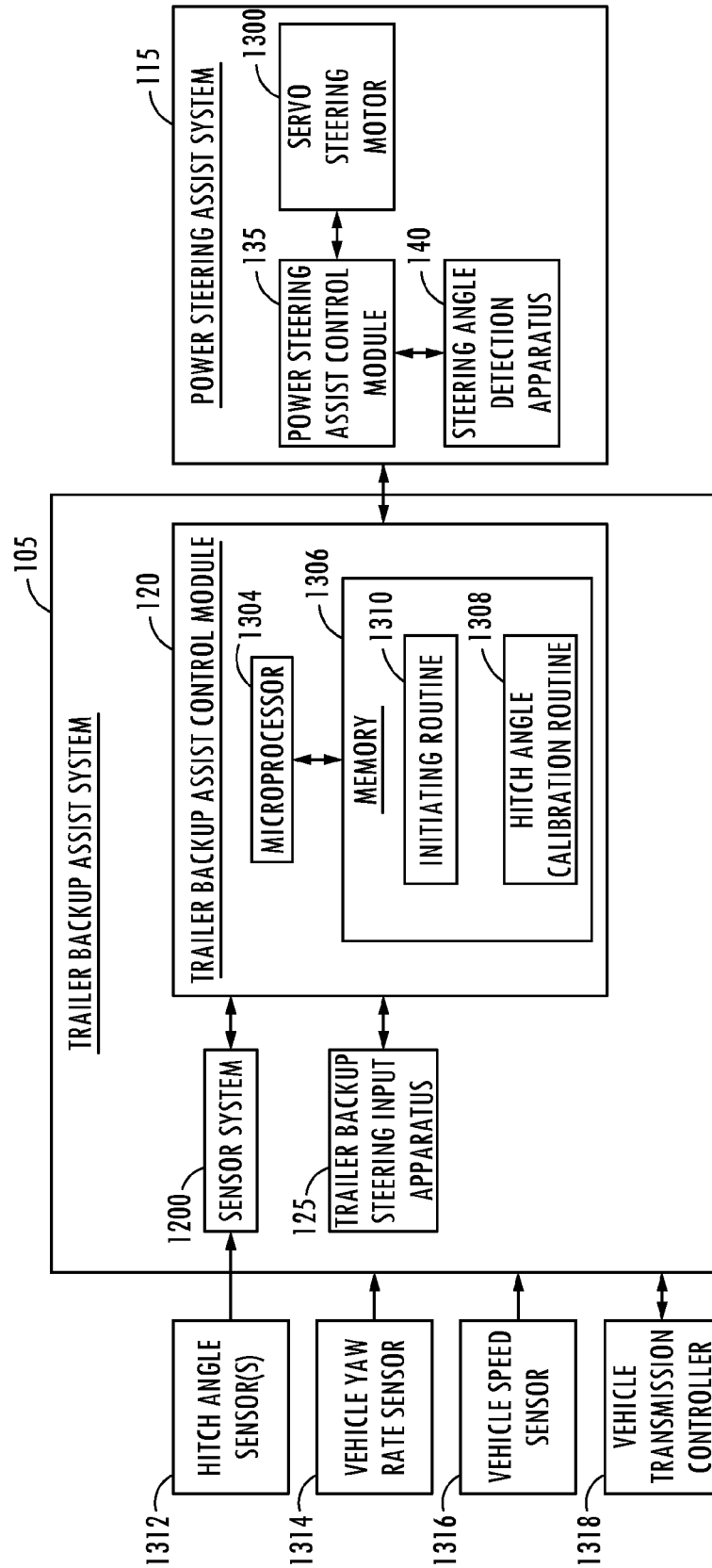
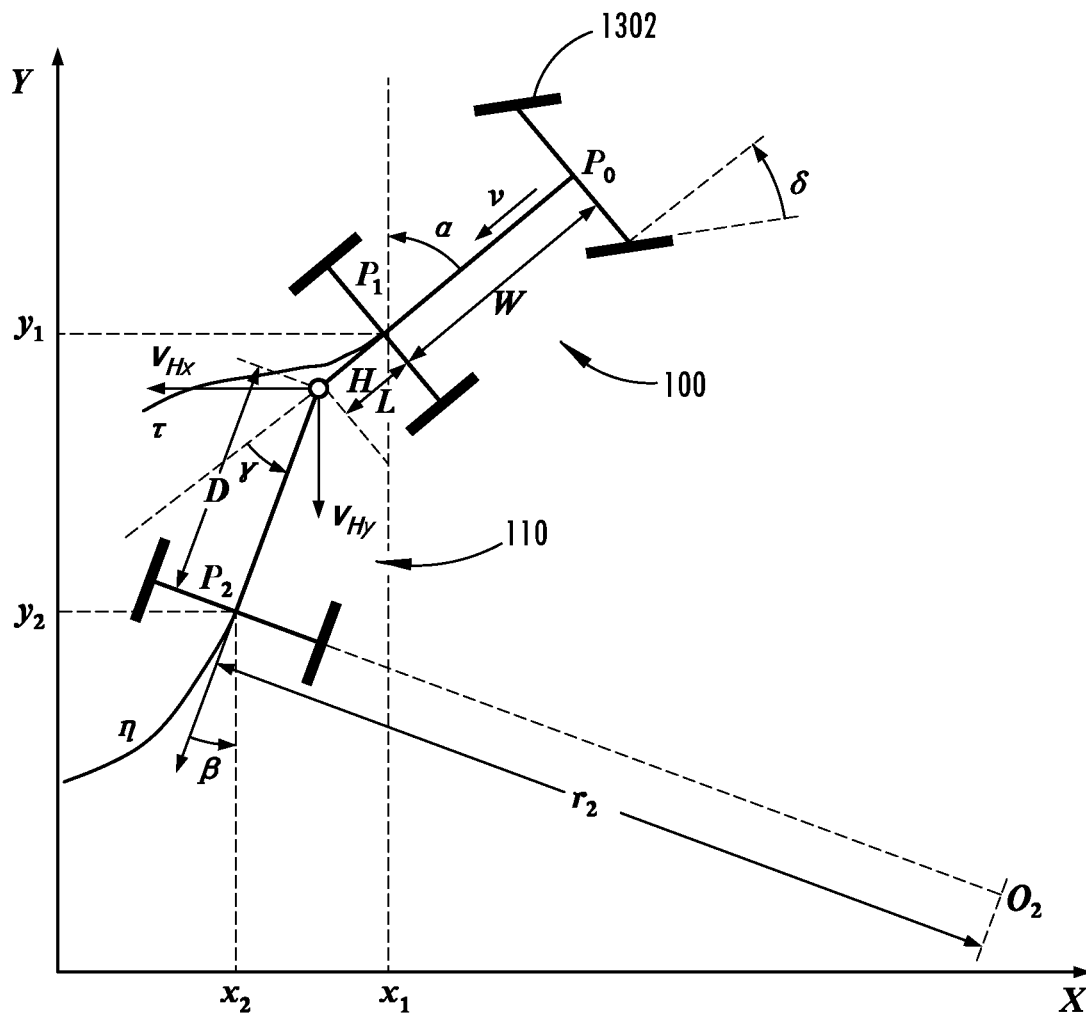
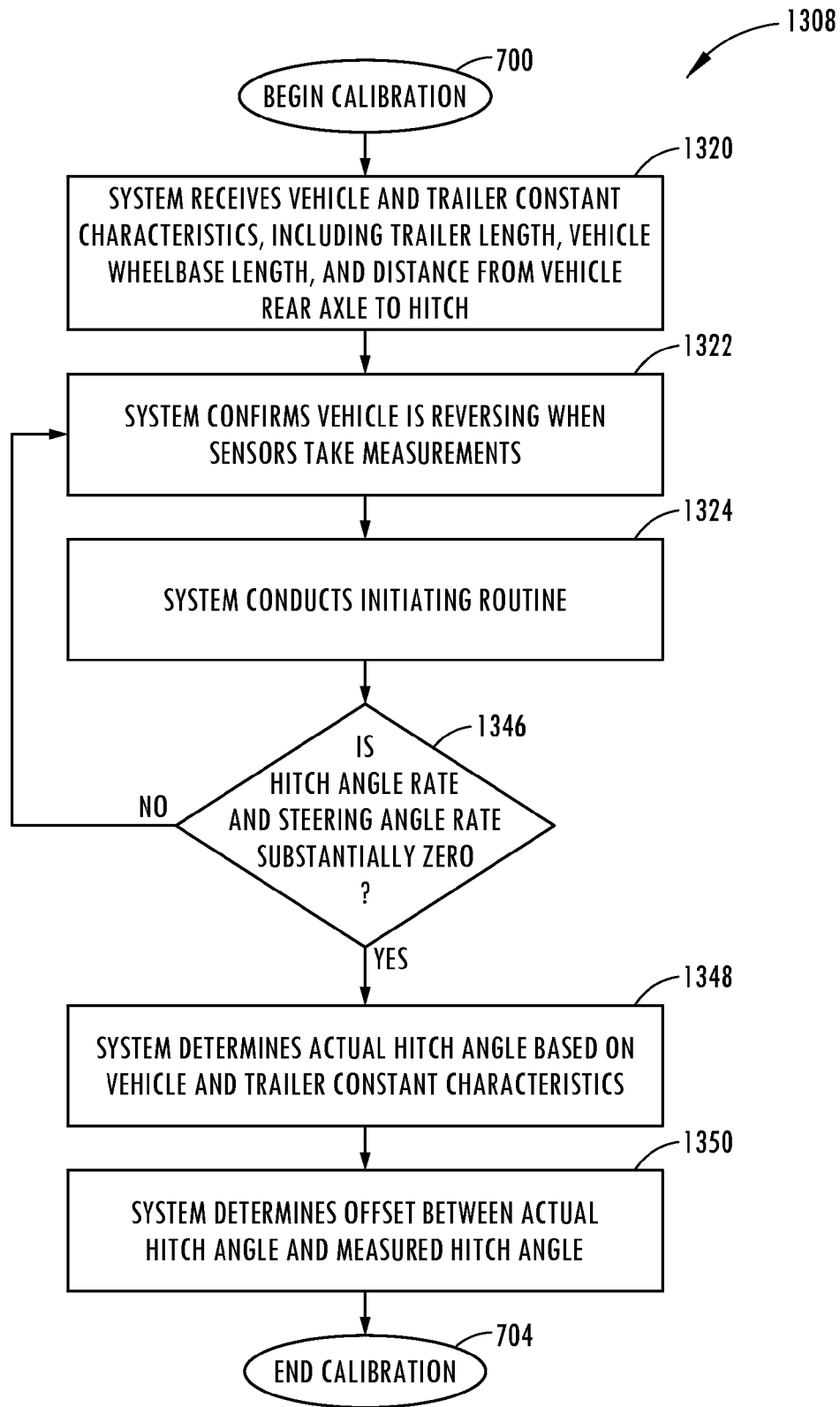


FIG. 35



**FIG. 36**

**FIG. 37**

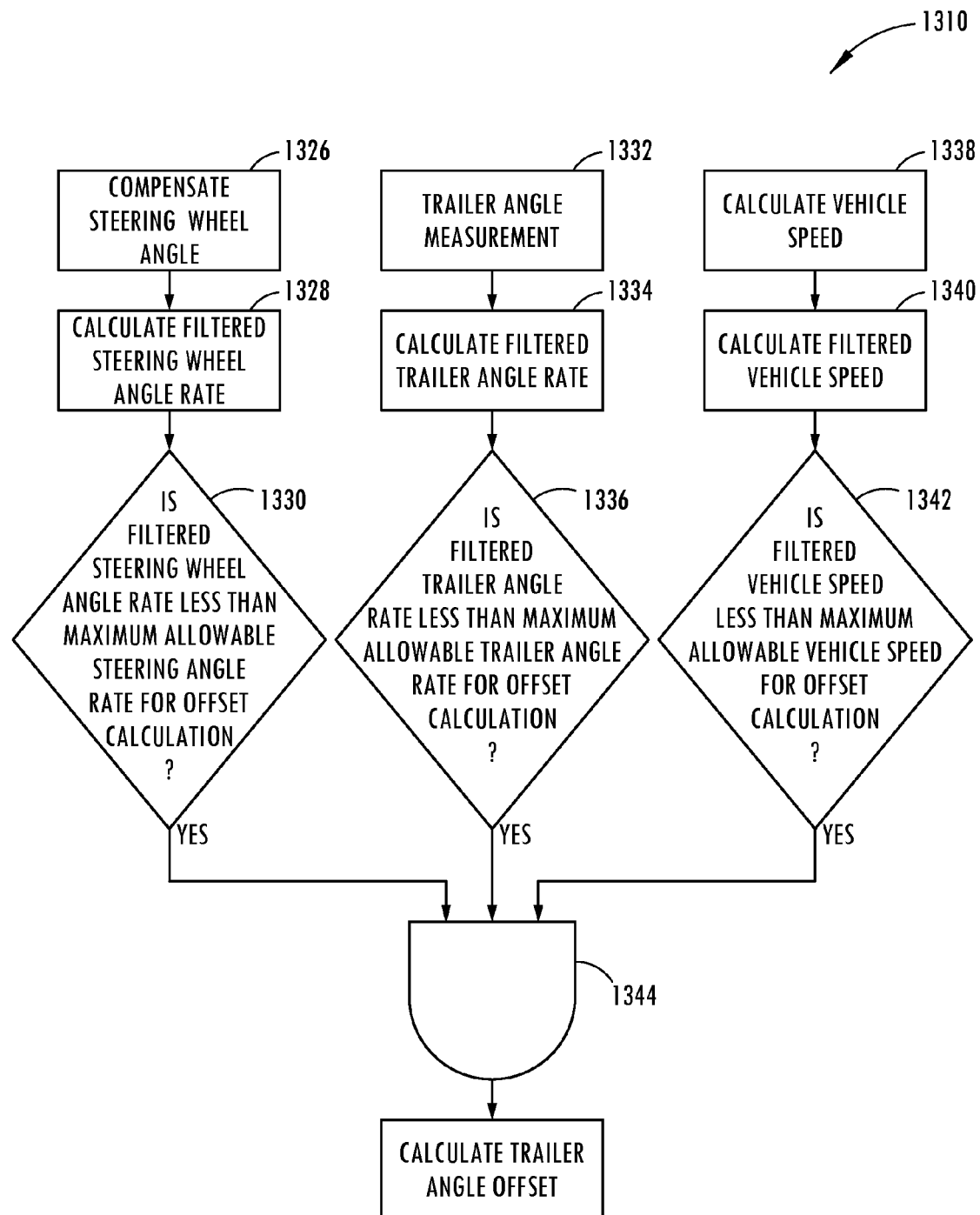
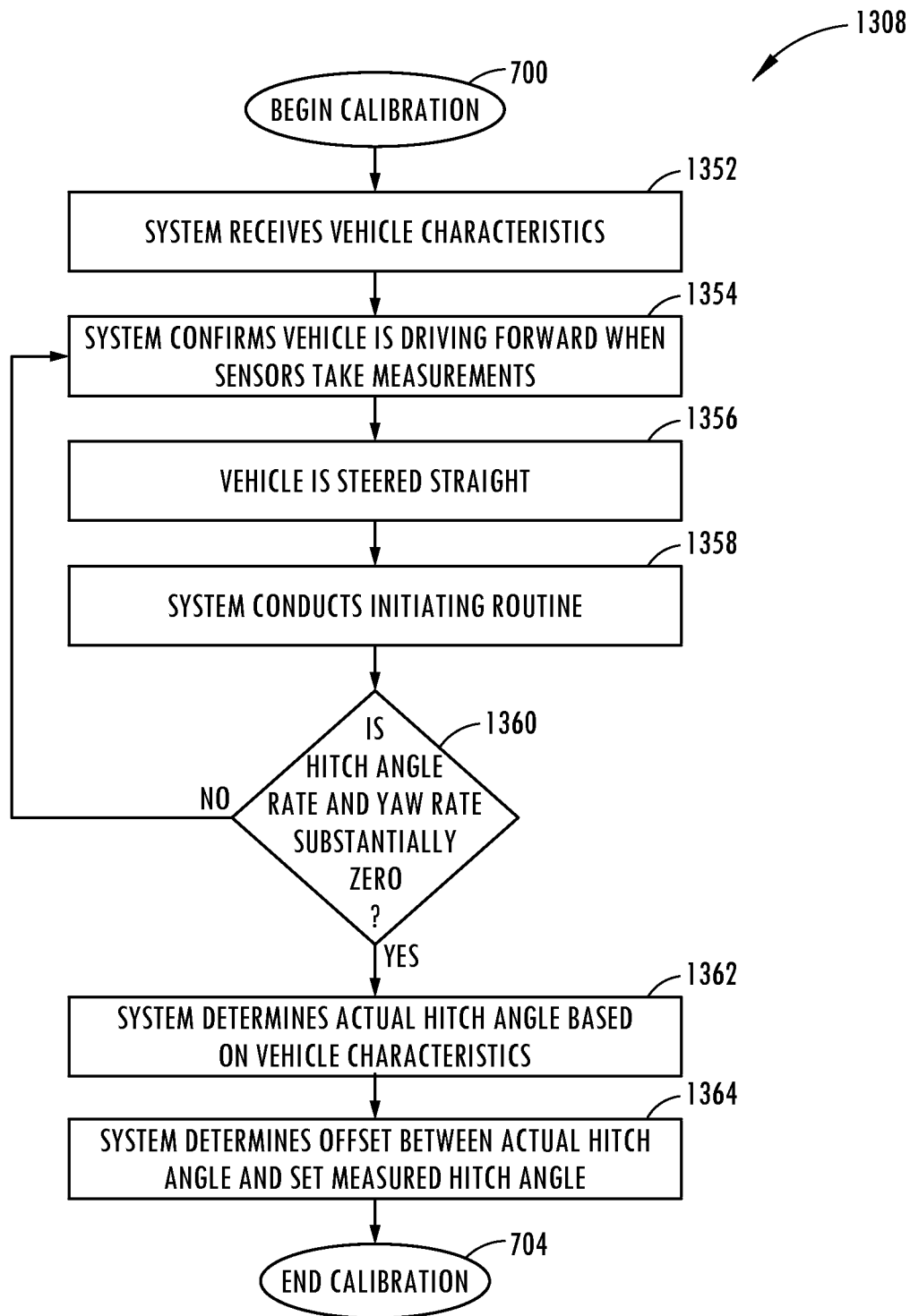


FIG. 38

**FIG. 39**

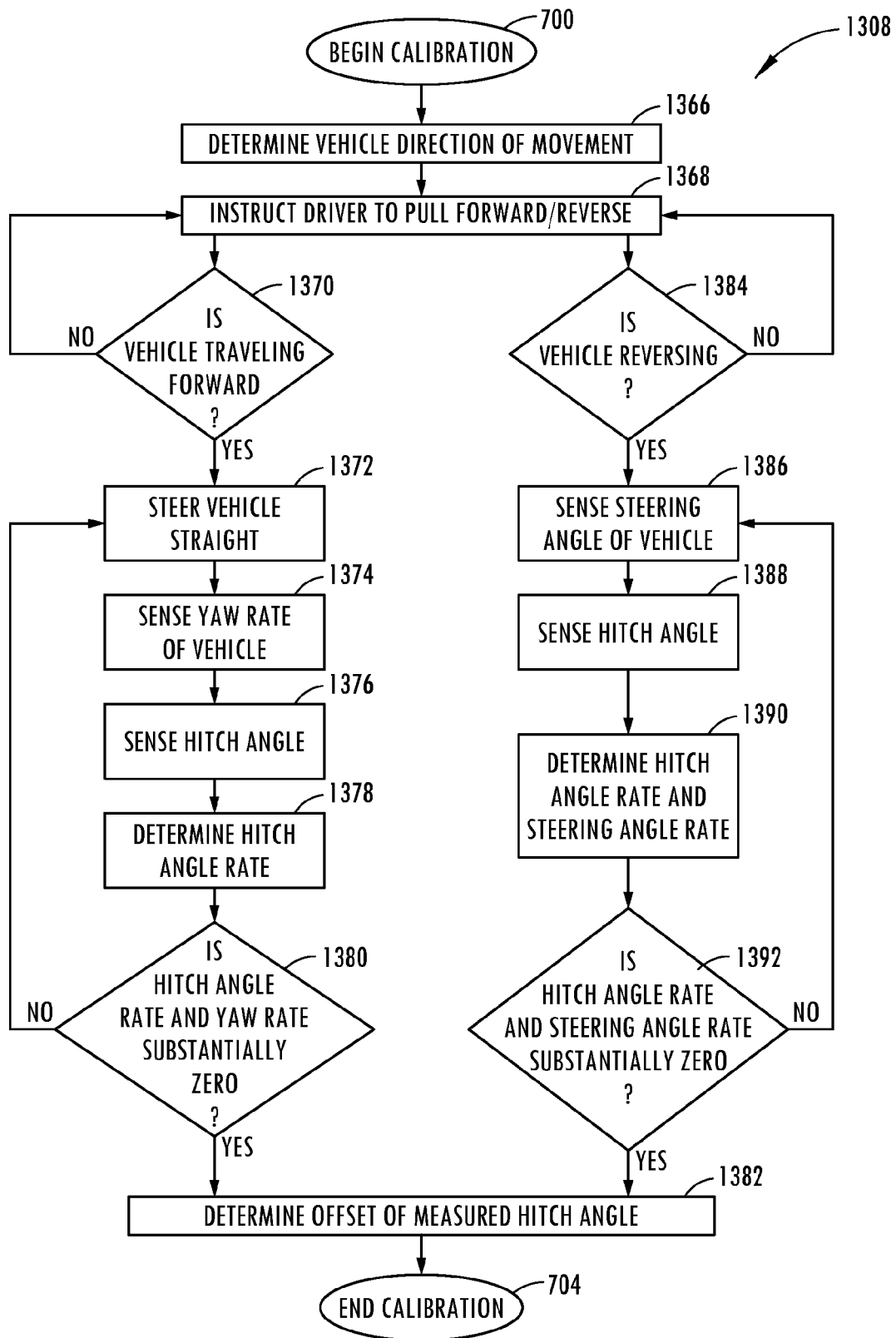


FIG. 40



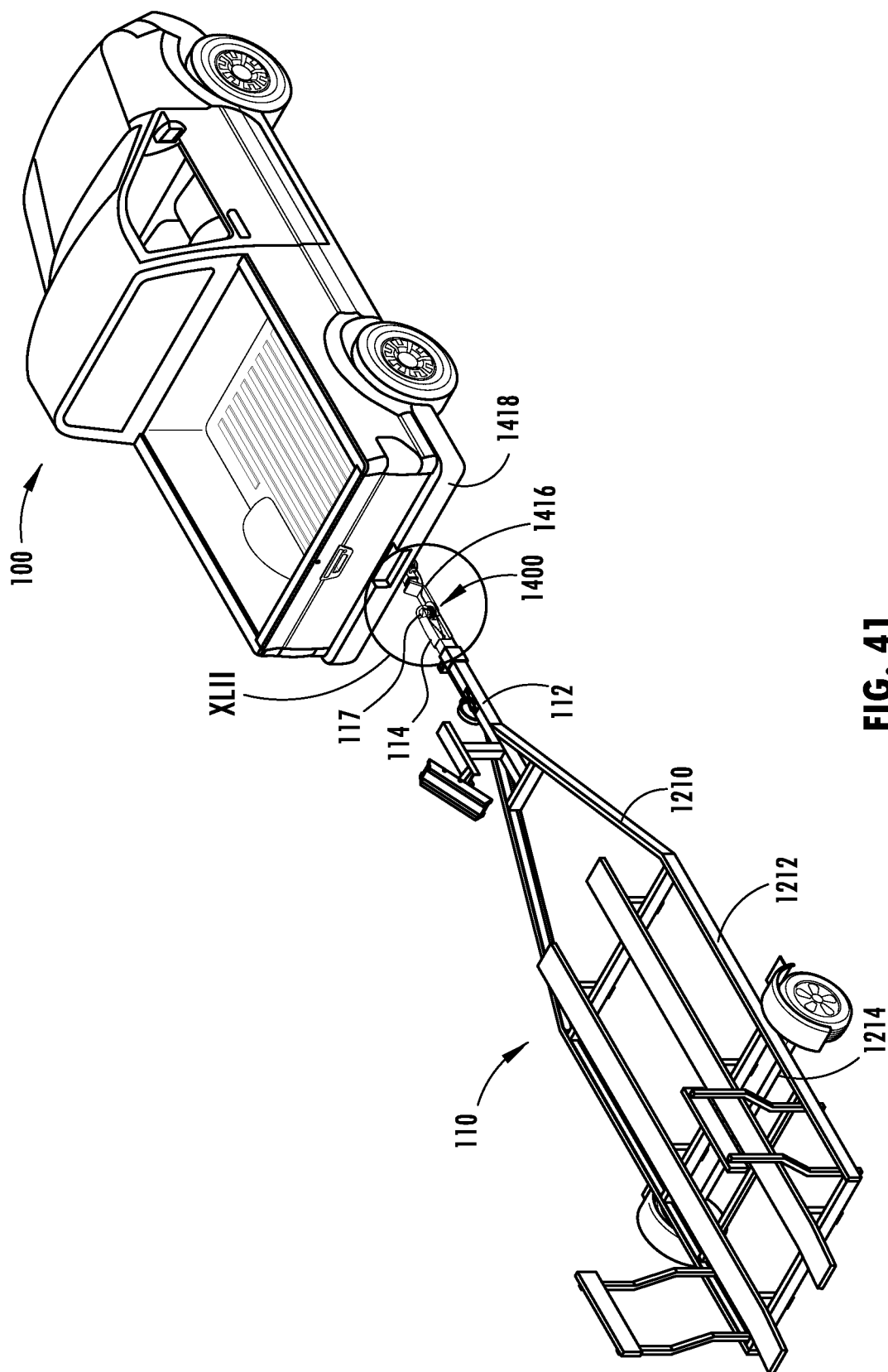


FIG. 41

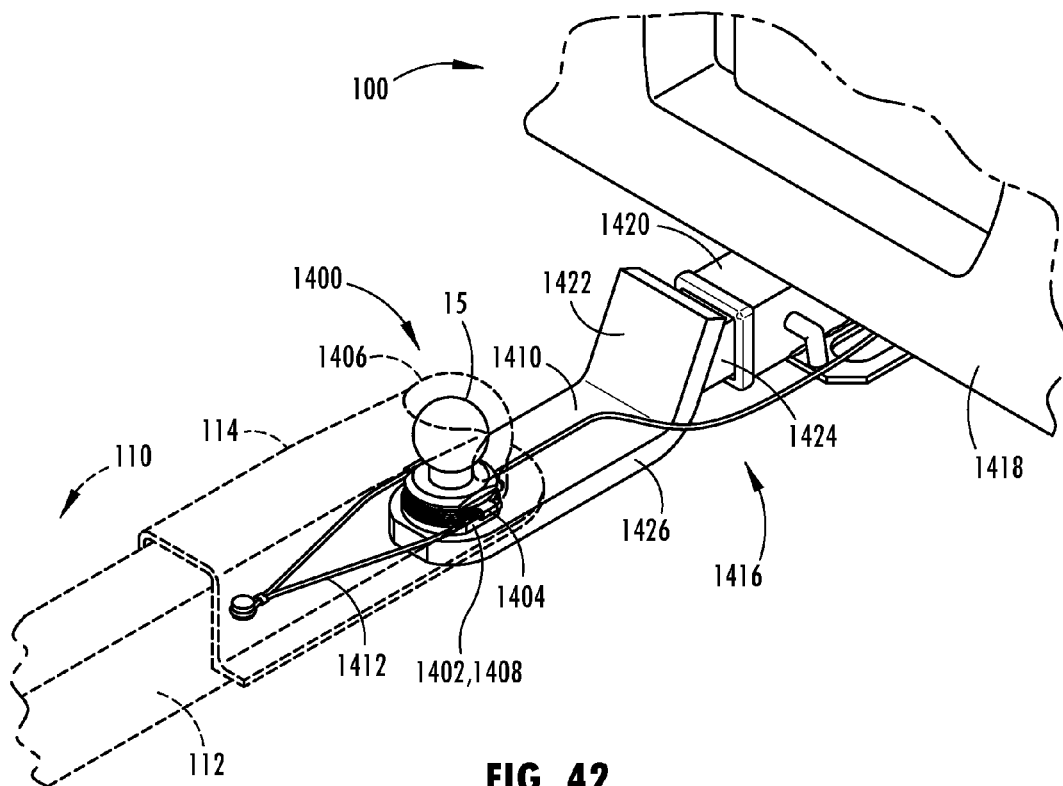


FIG. 42

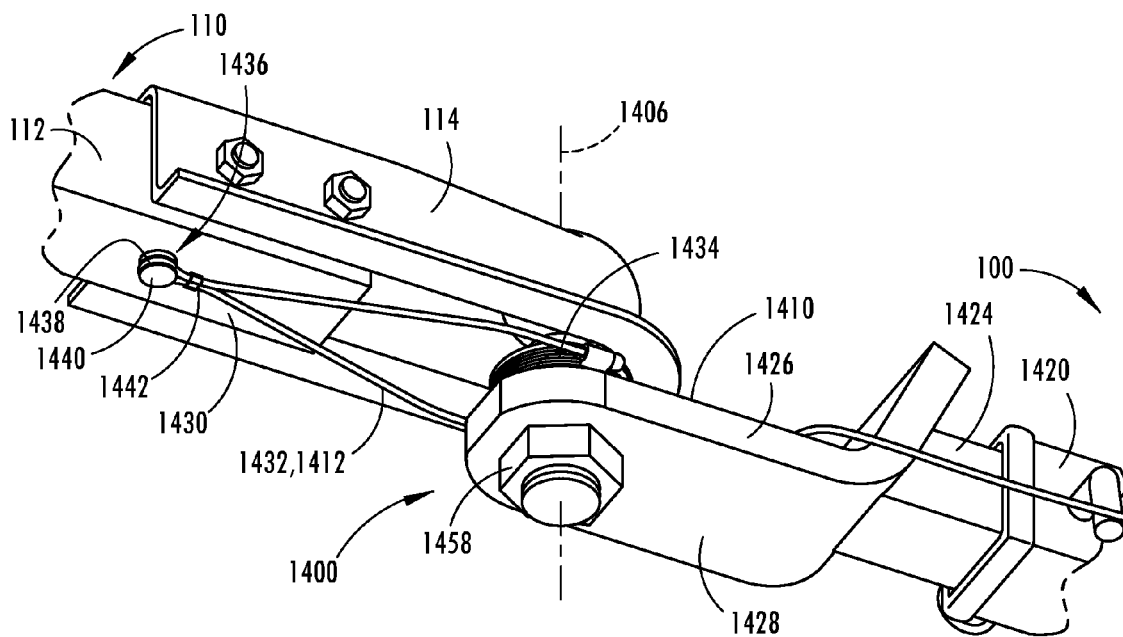
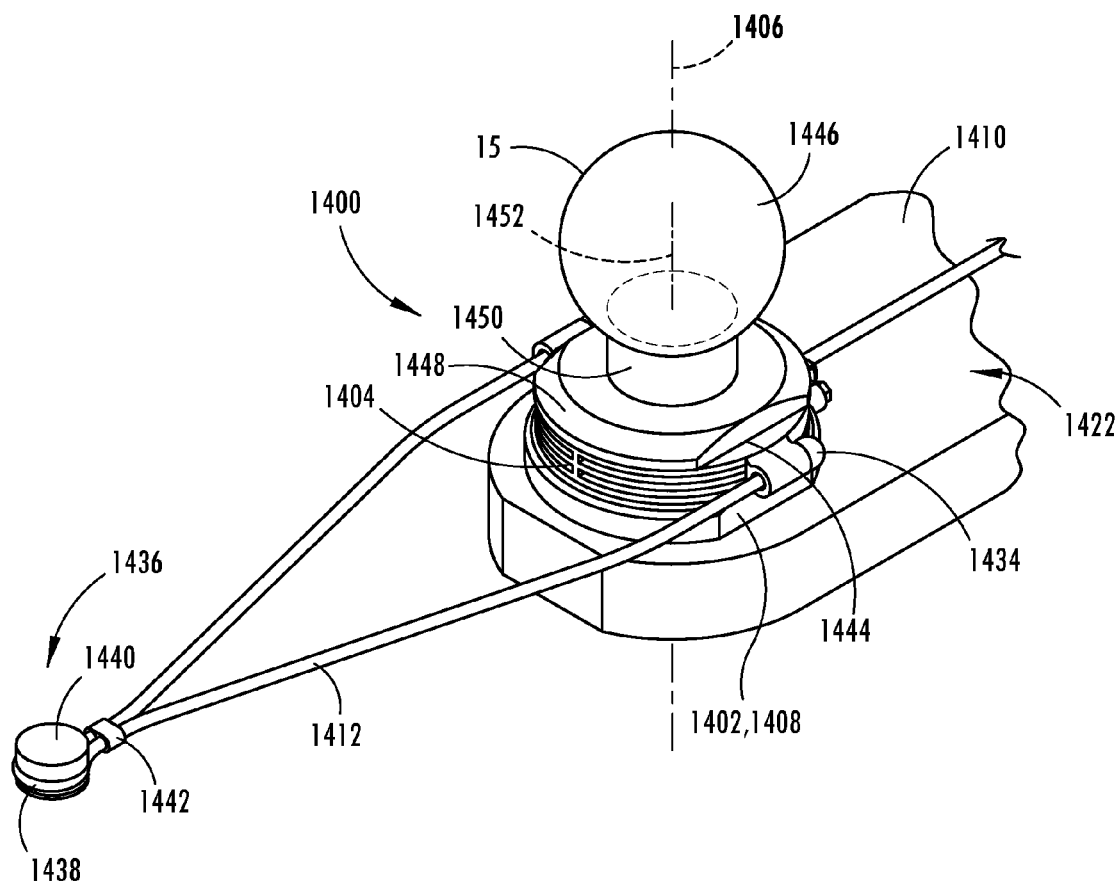


FIG. 42A



**FIG. 43**

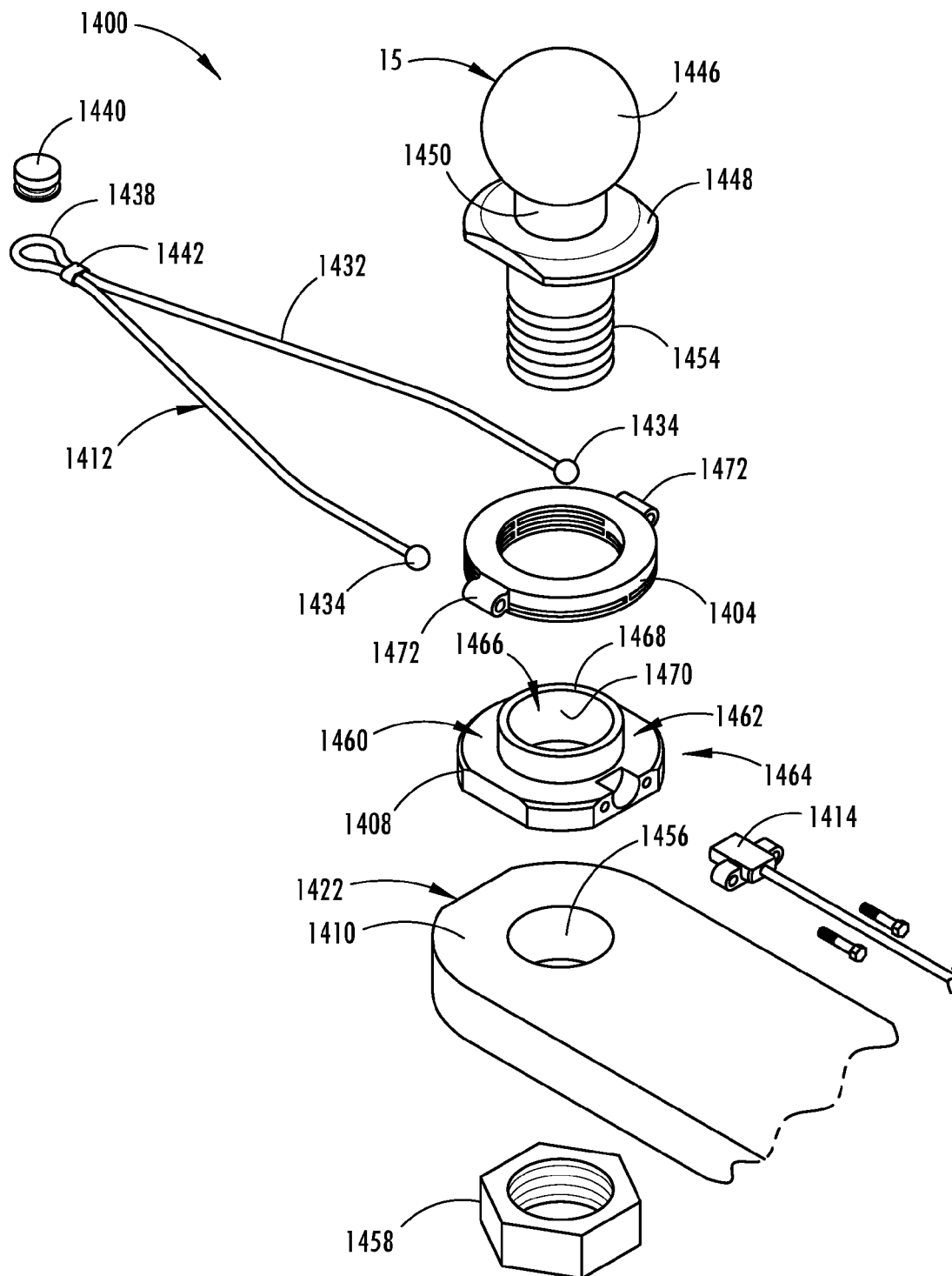


FIG. 44

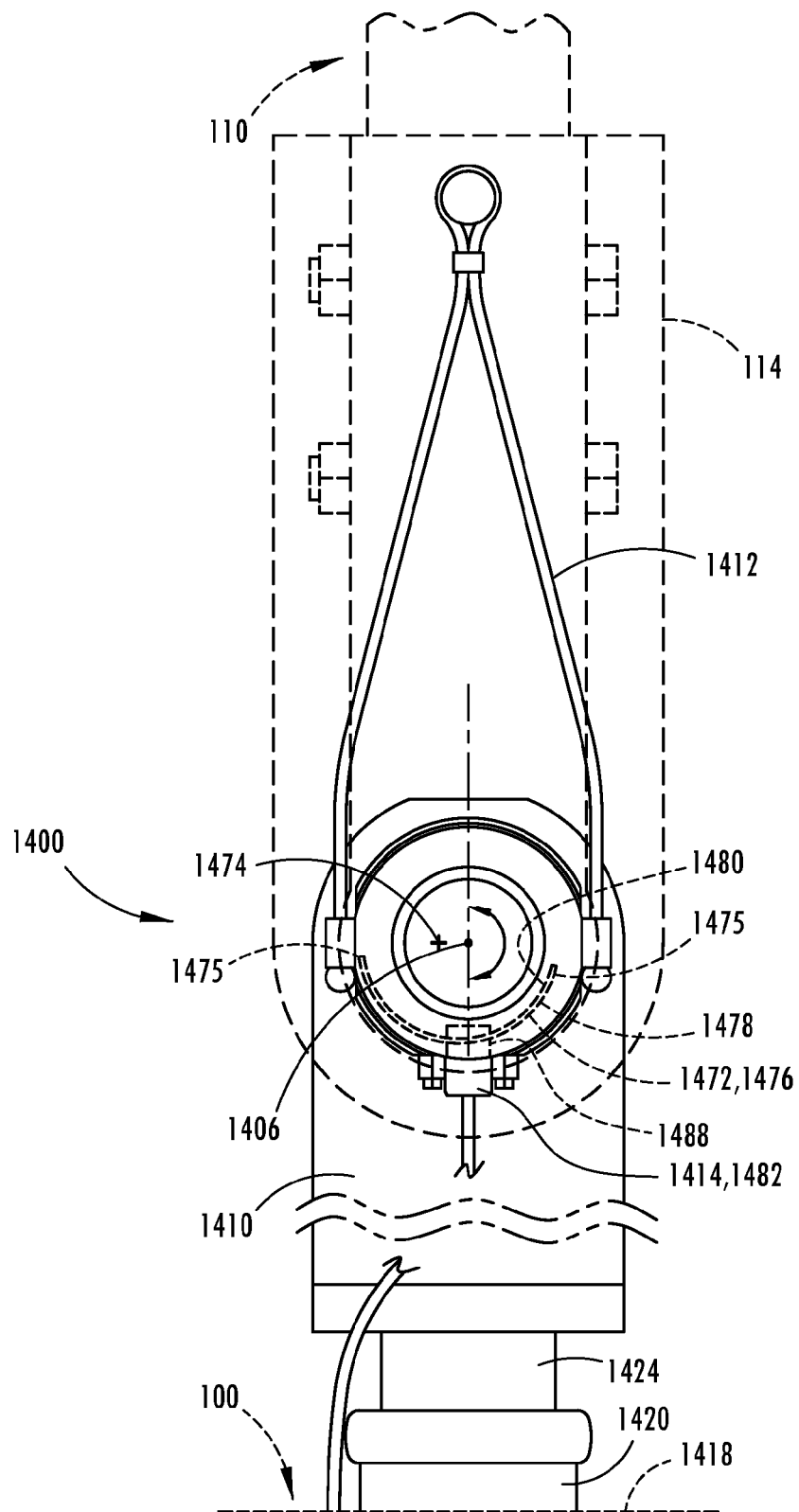


FIG. 45

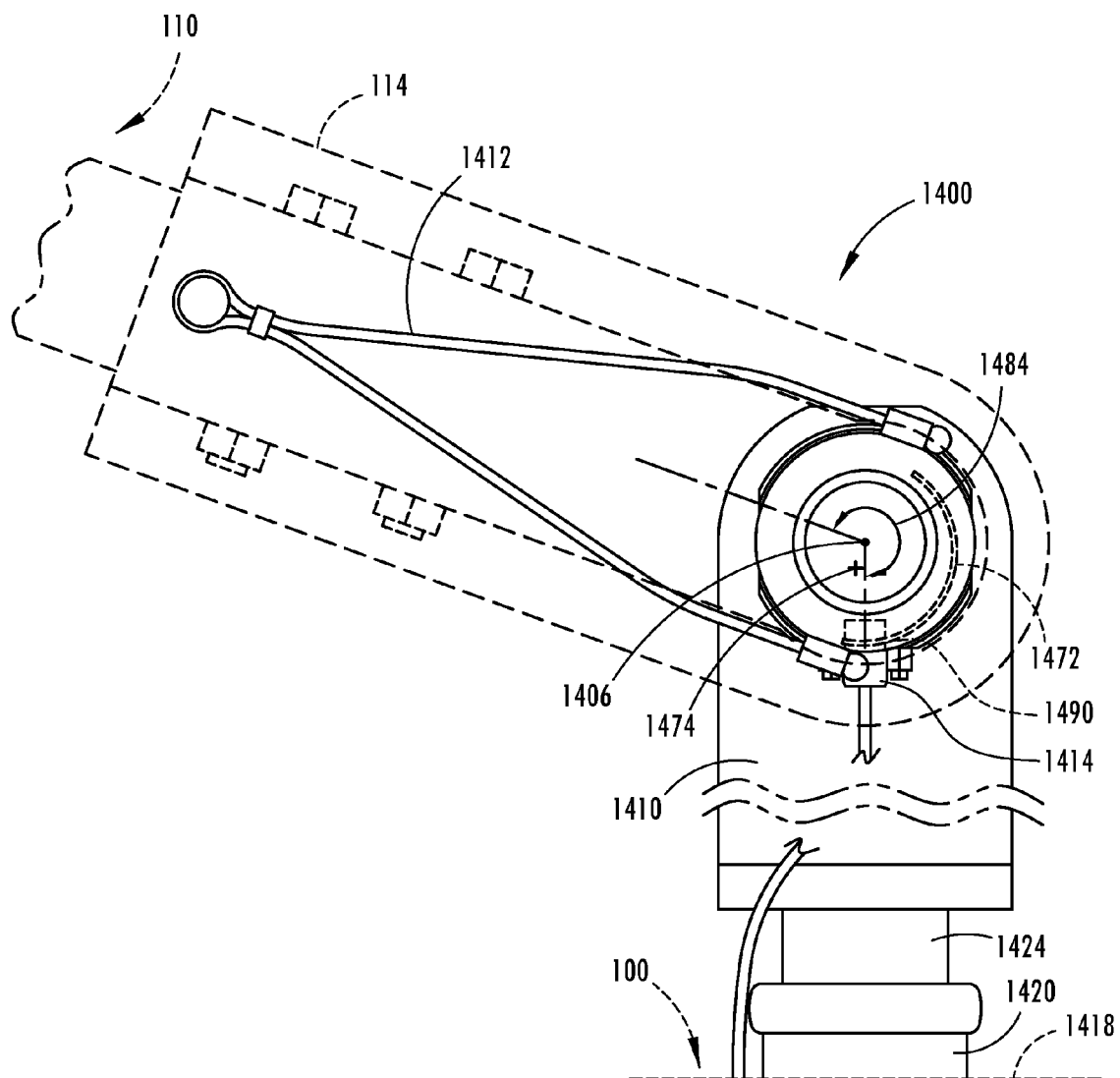


FIG. 46

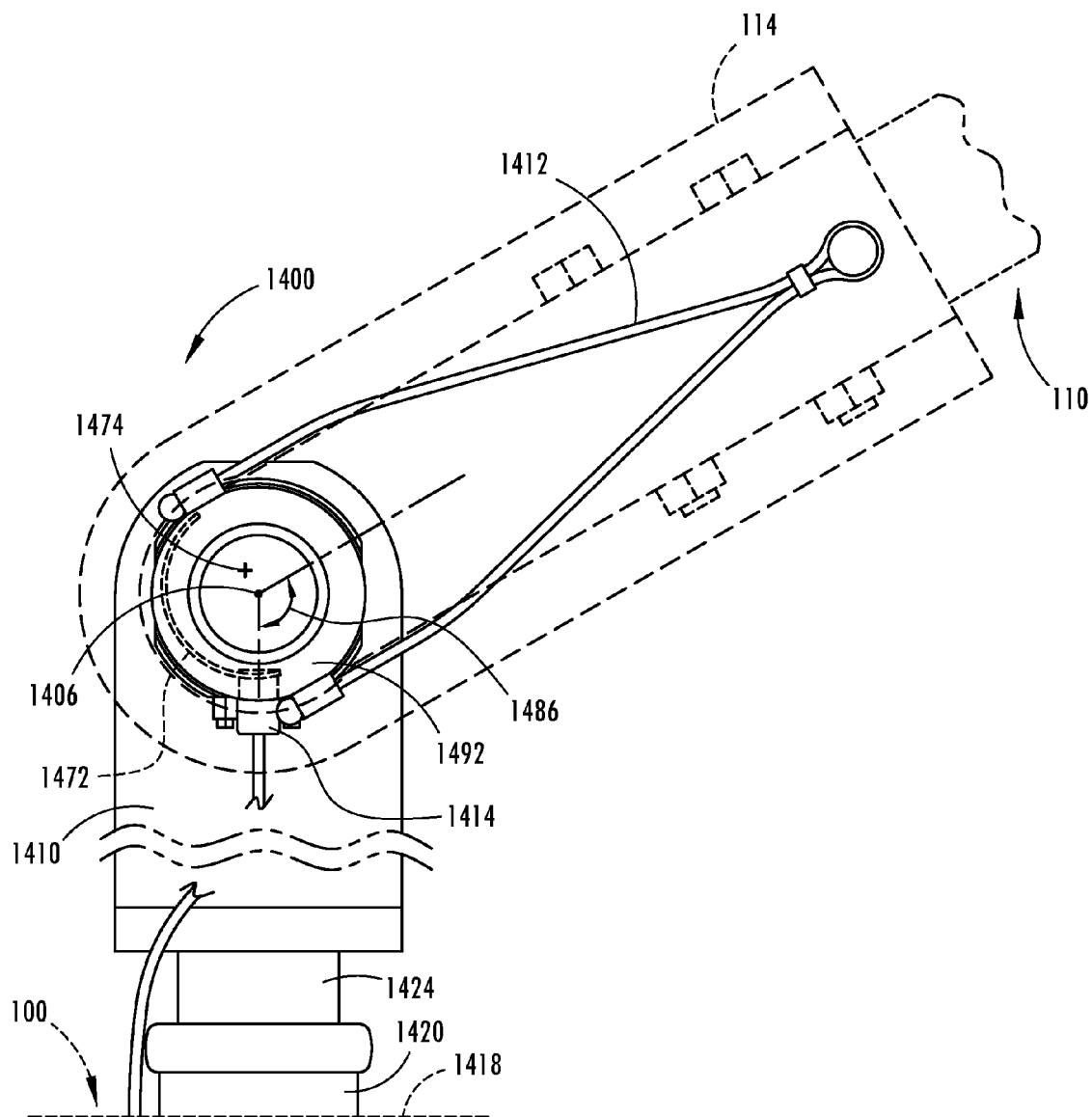
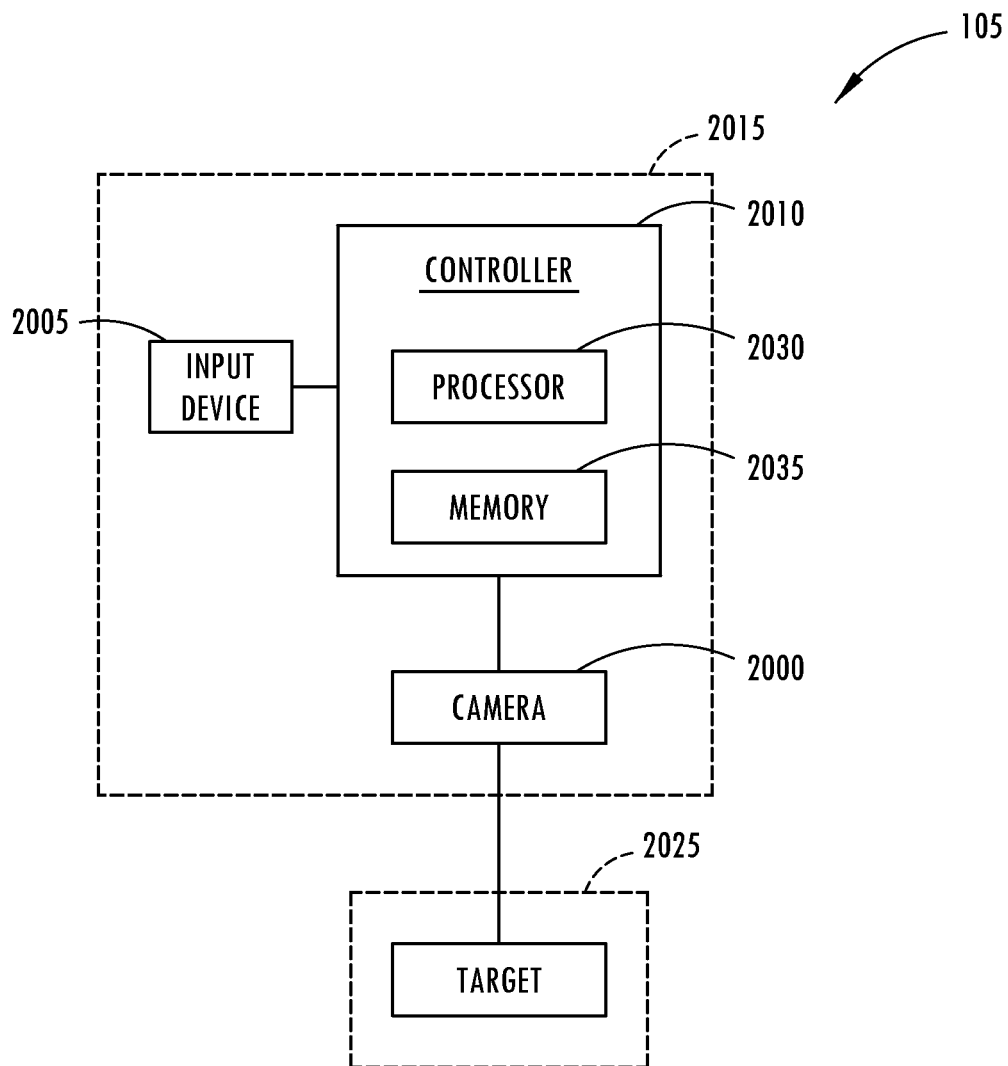


FIG. 47



**FIG. 48**



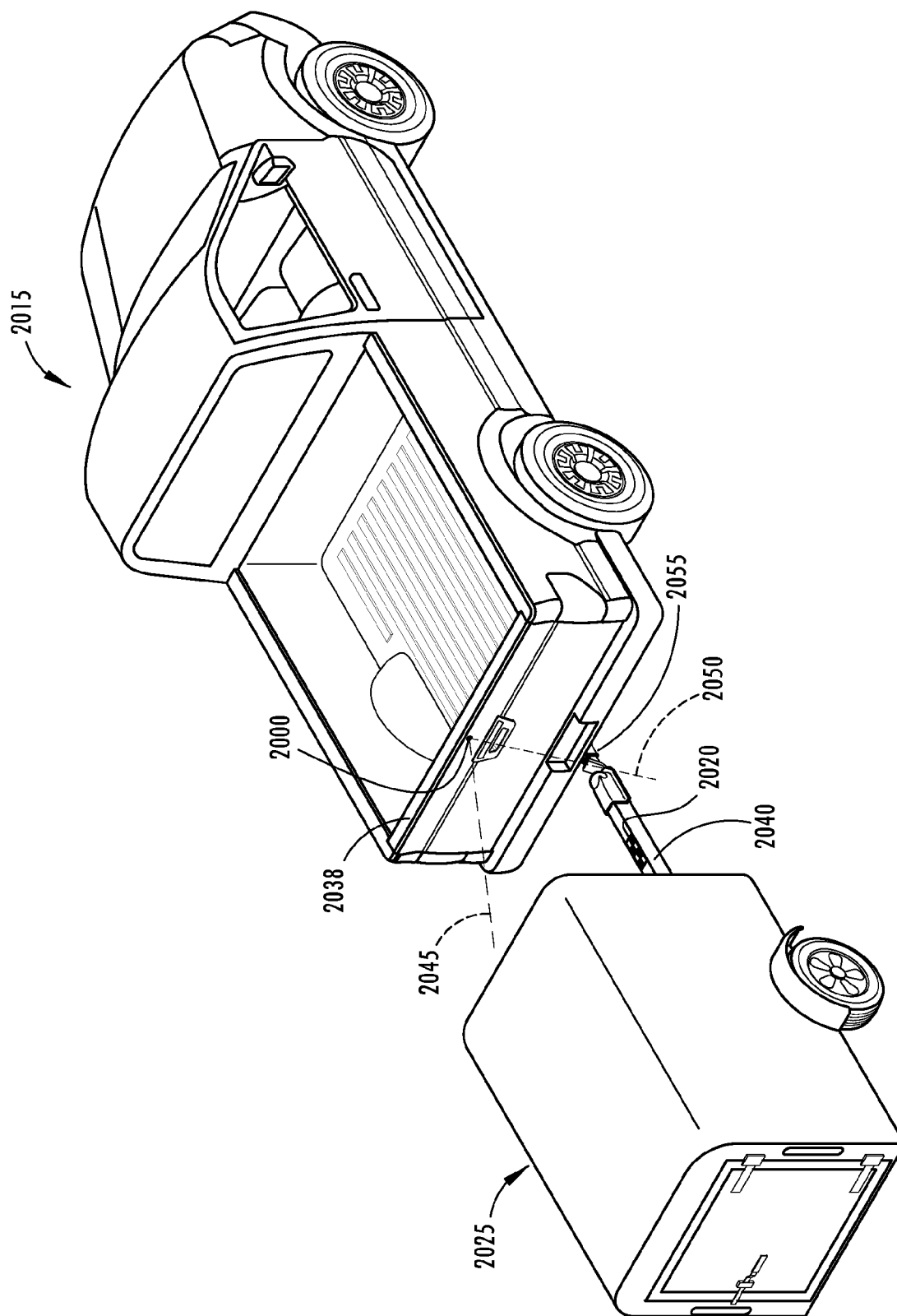


FIG. 49

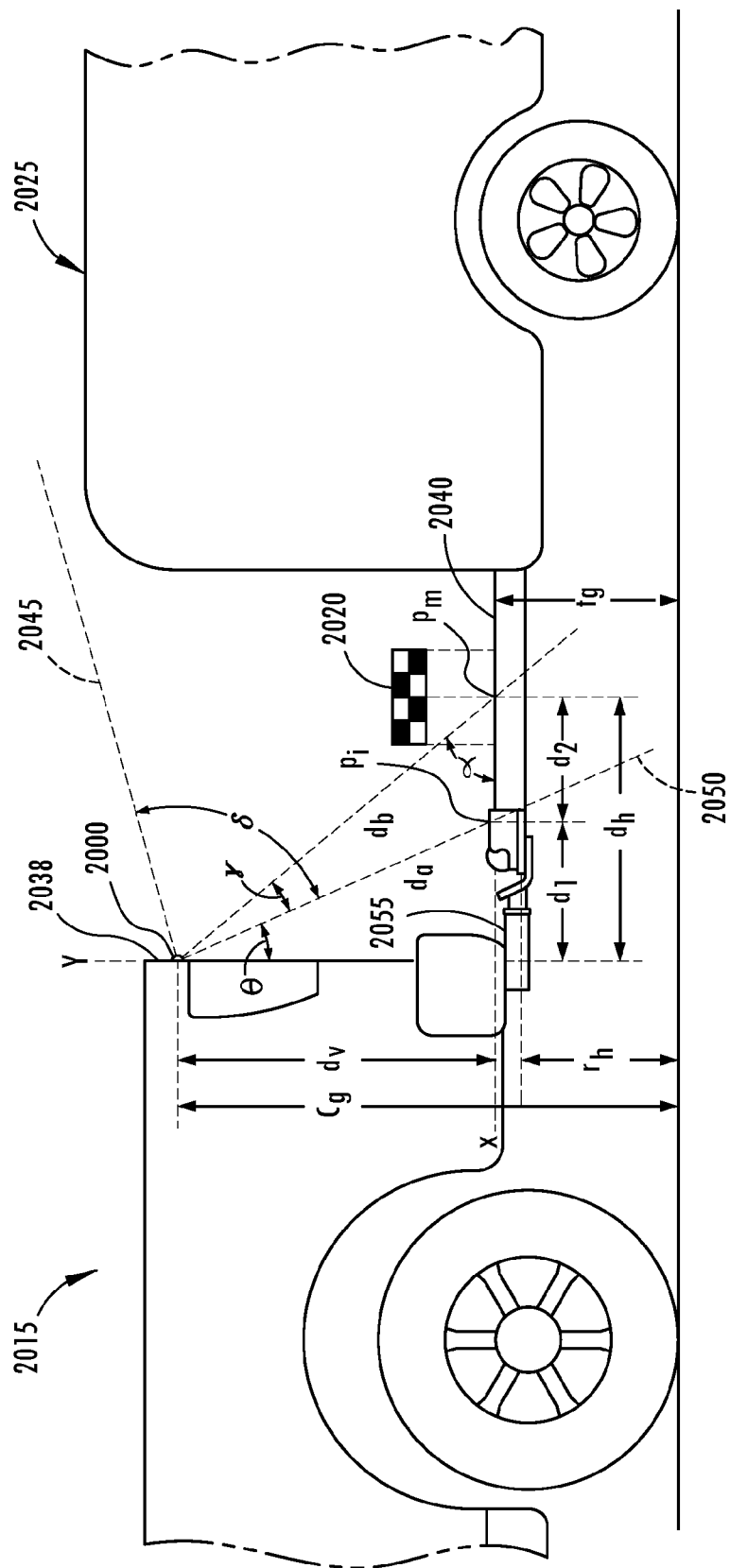
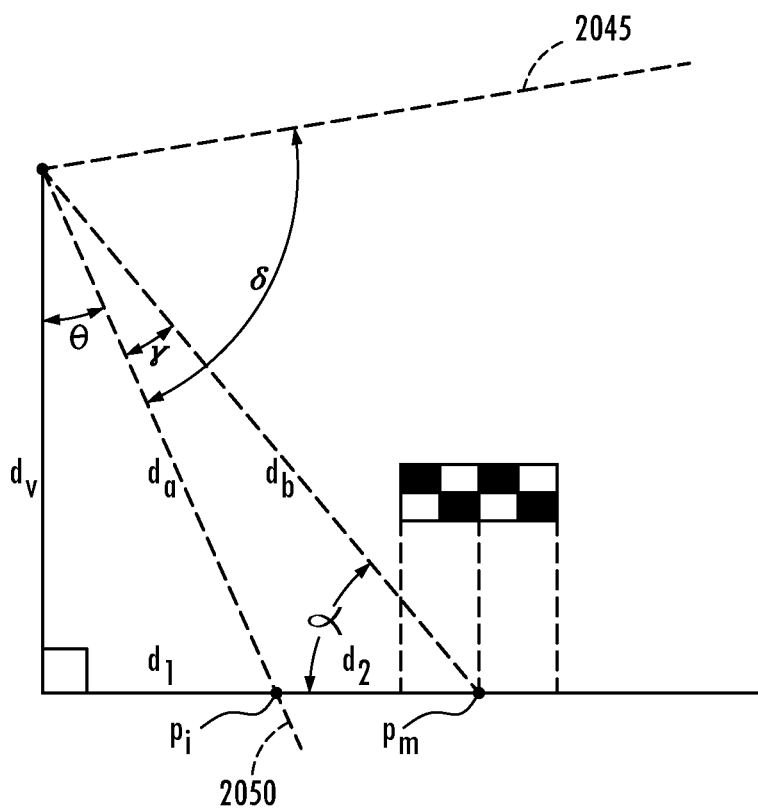


FIG. 50



**FIG. 51**

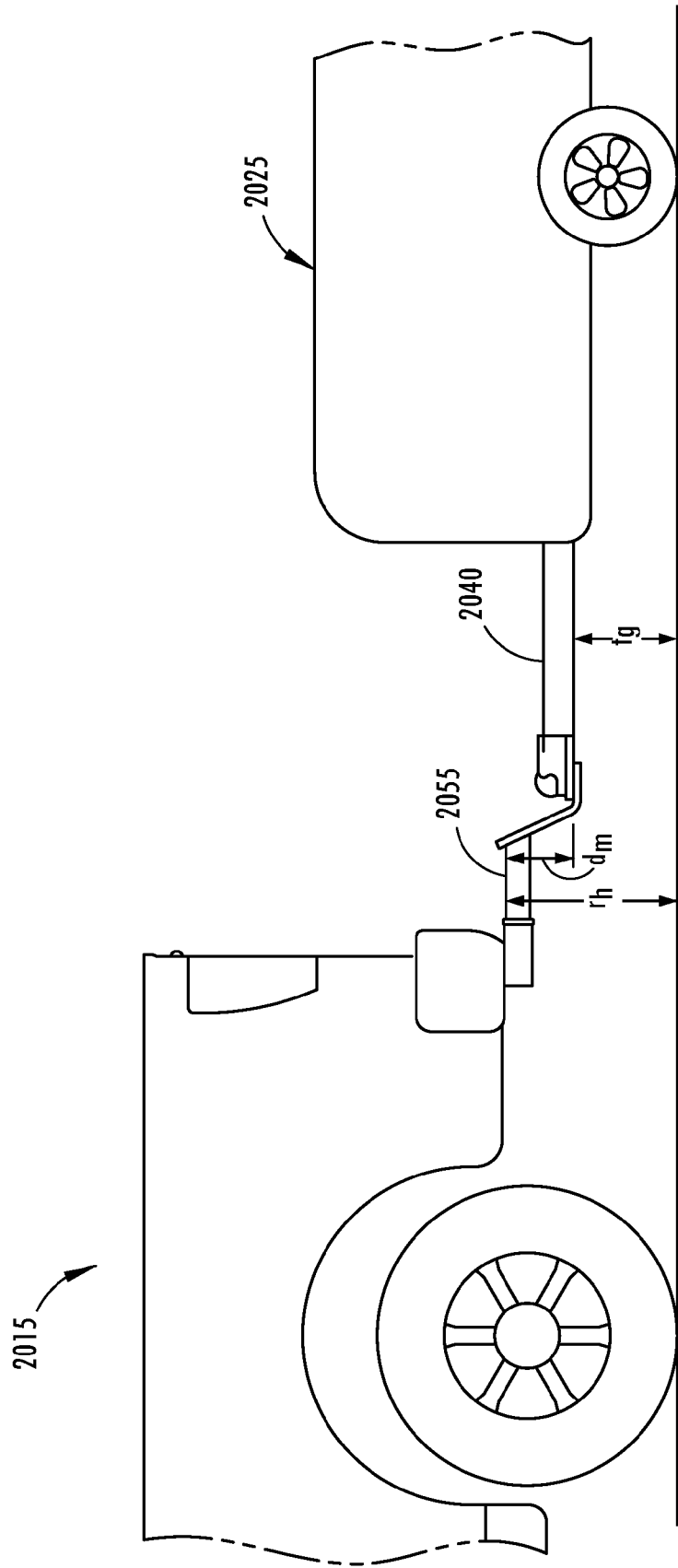
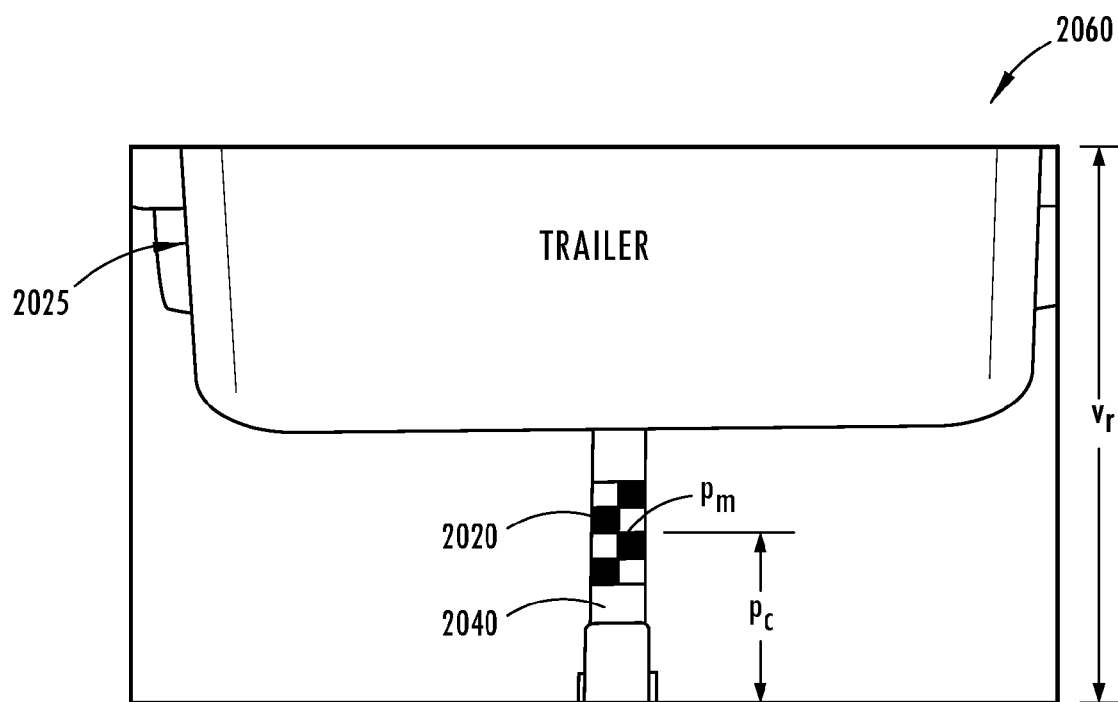


FIG. 52



**FIG. 53**

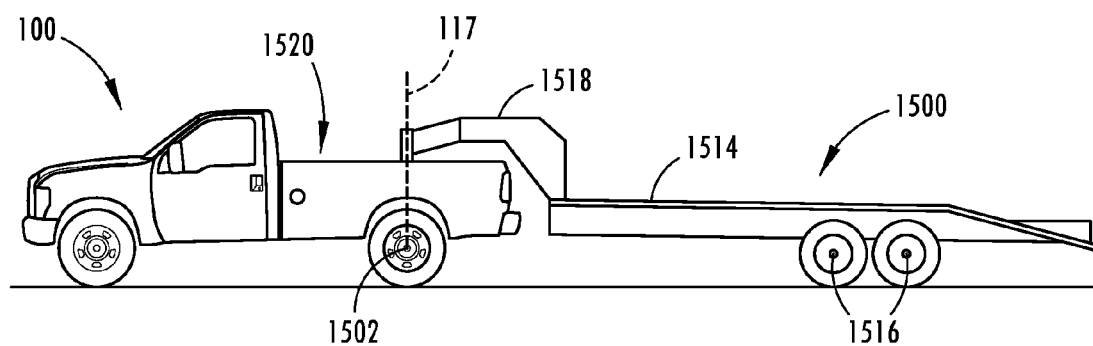


FIG. 54

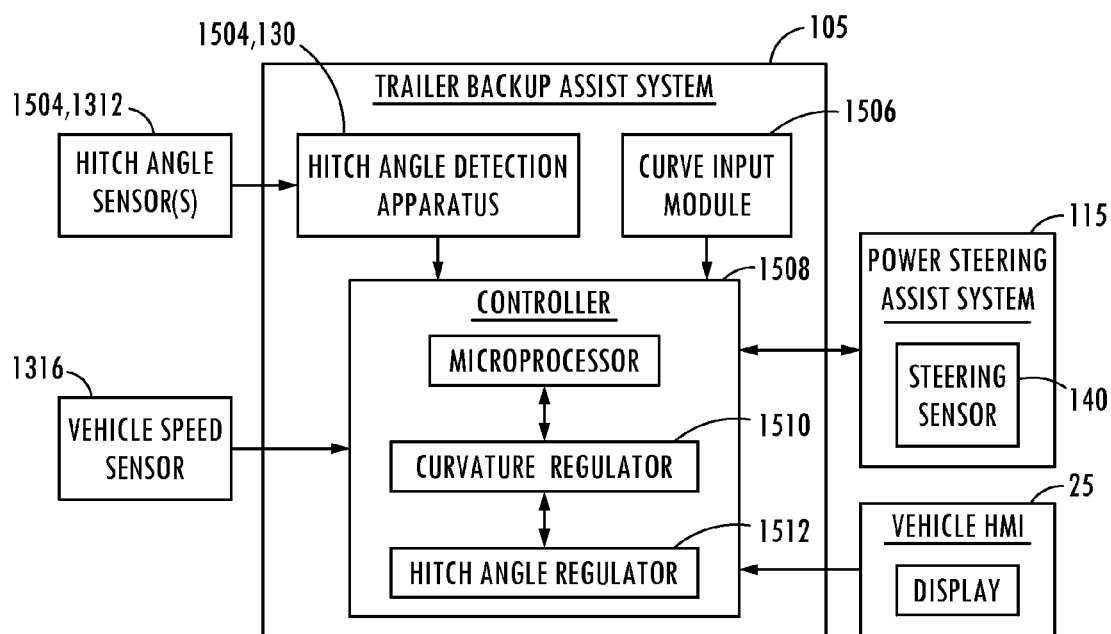
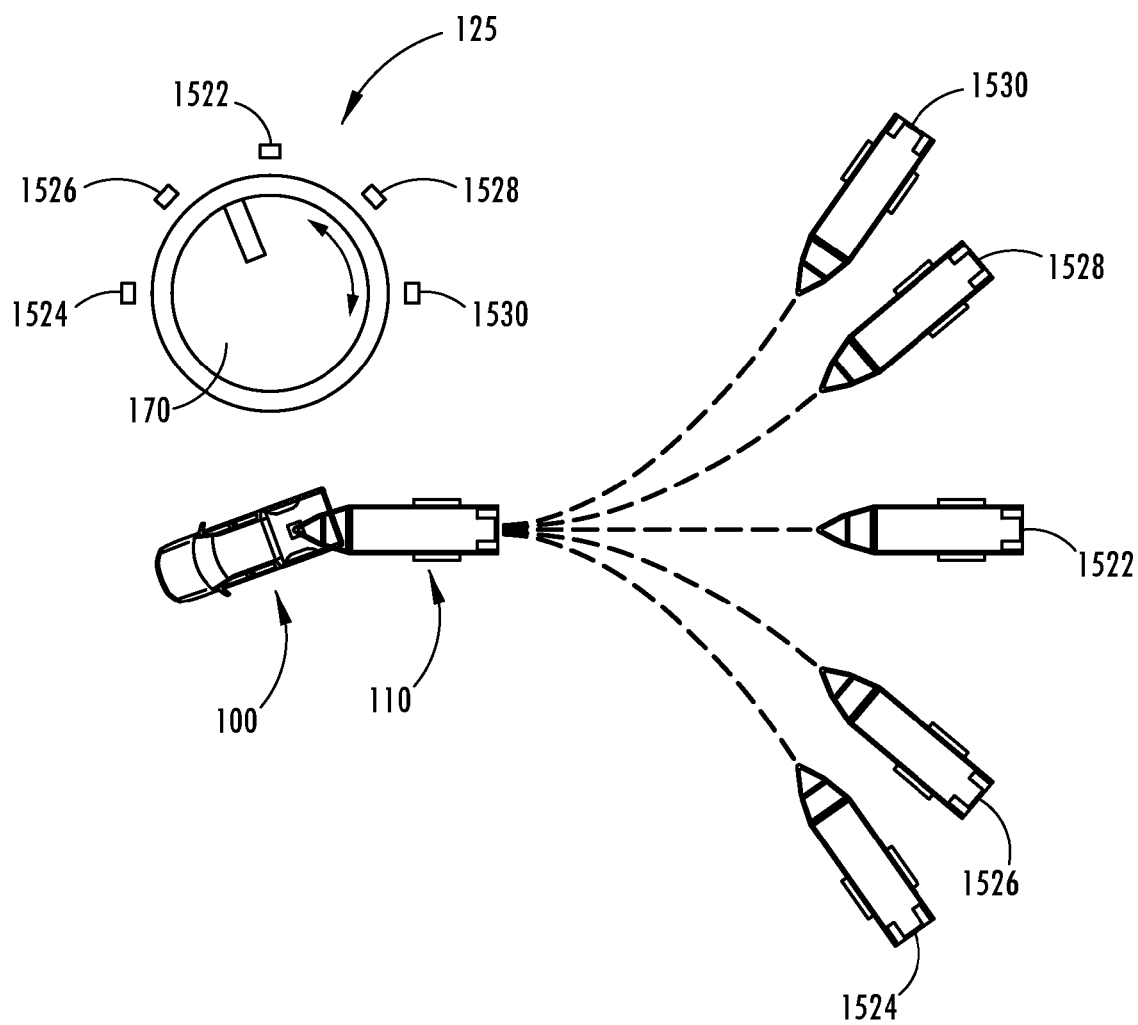


FIG. 55



**FIG. 56**

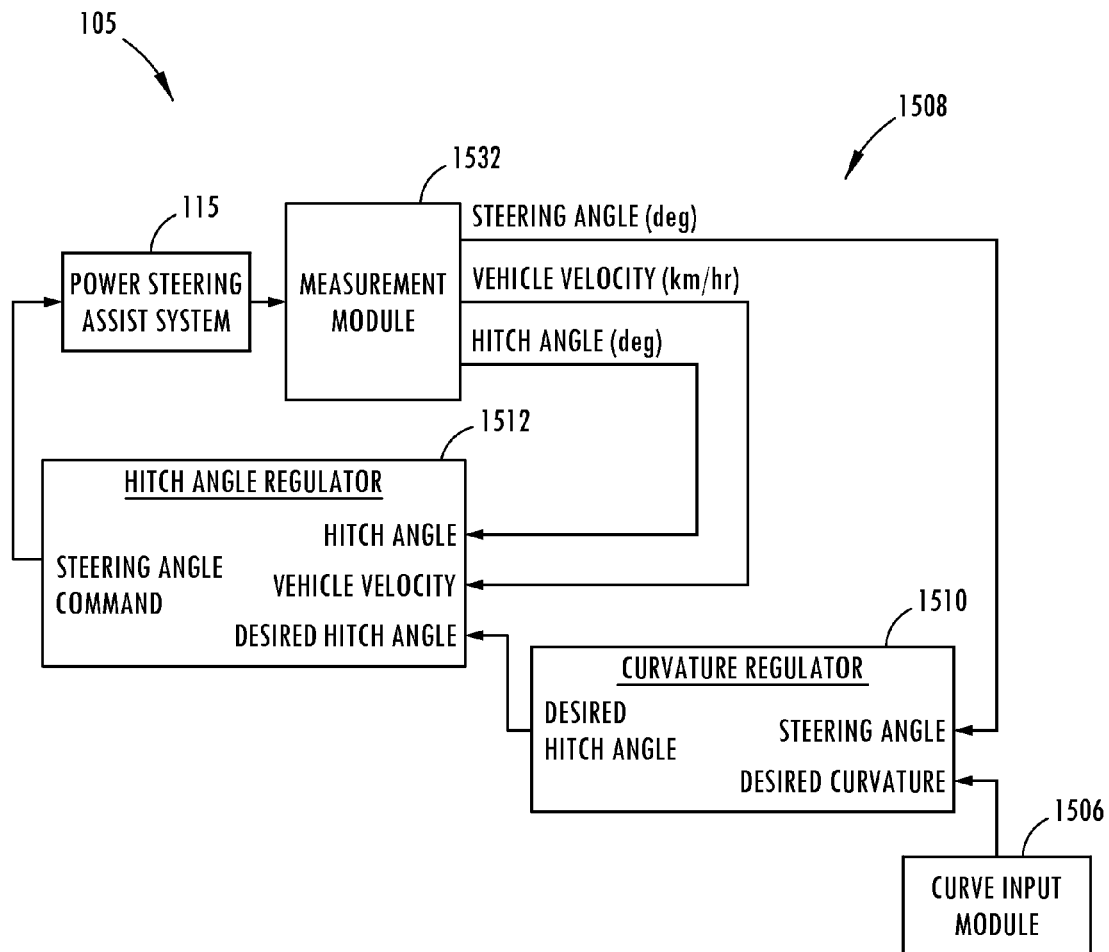


FIG. 57

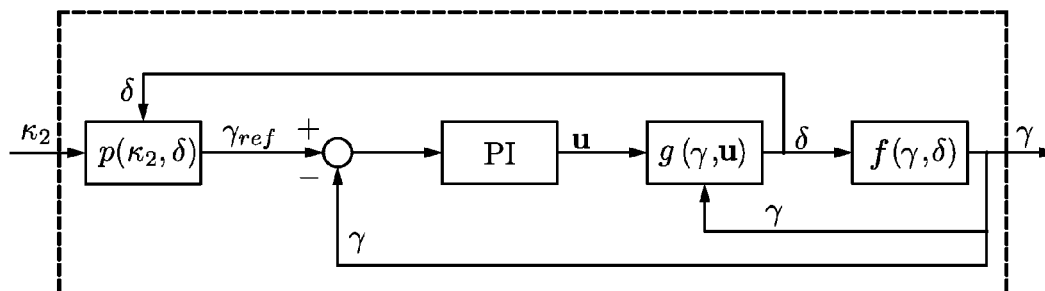
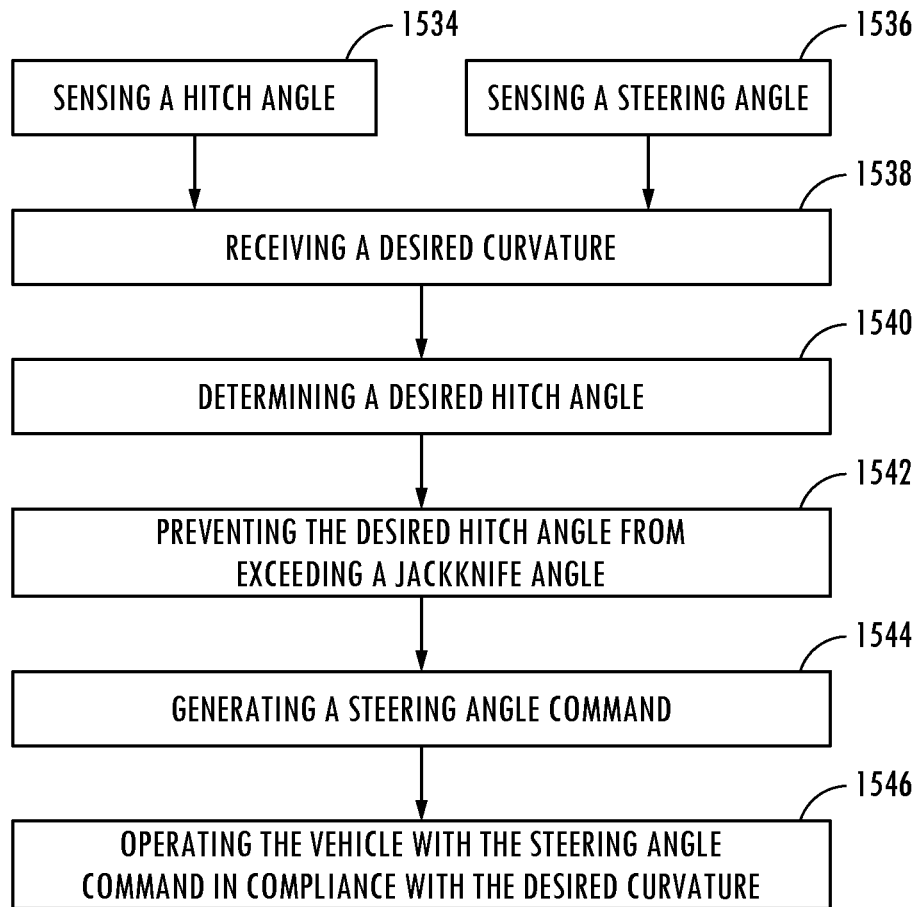


FIG. 58



**FIG. 59**

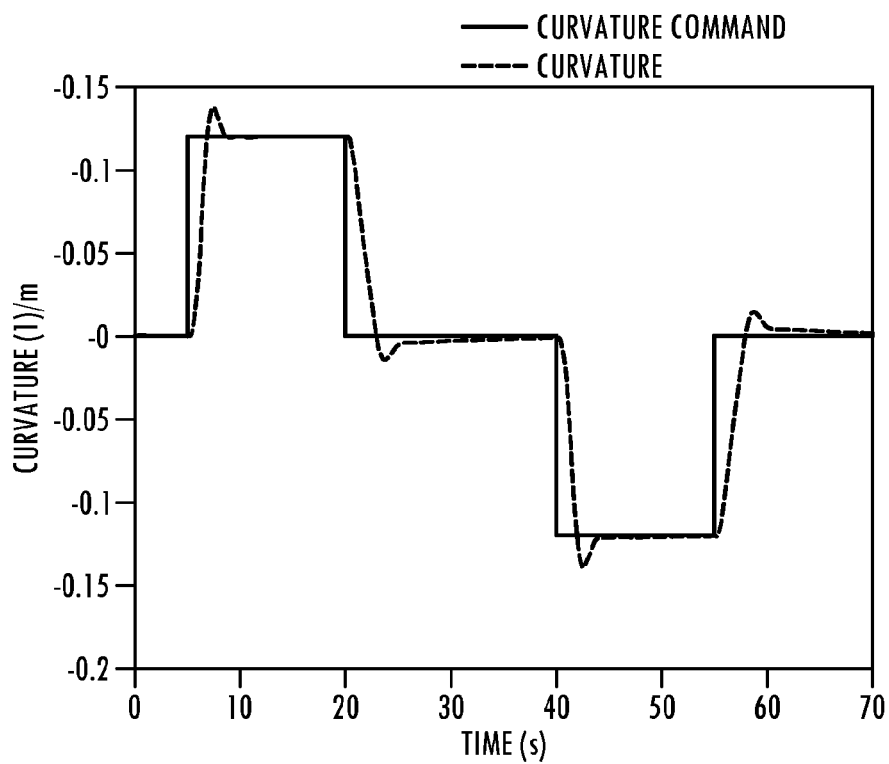


FIG. 60A

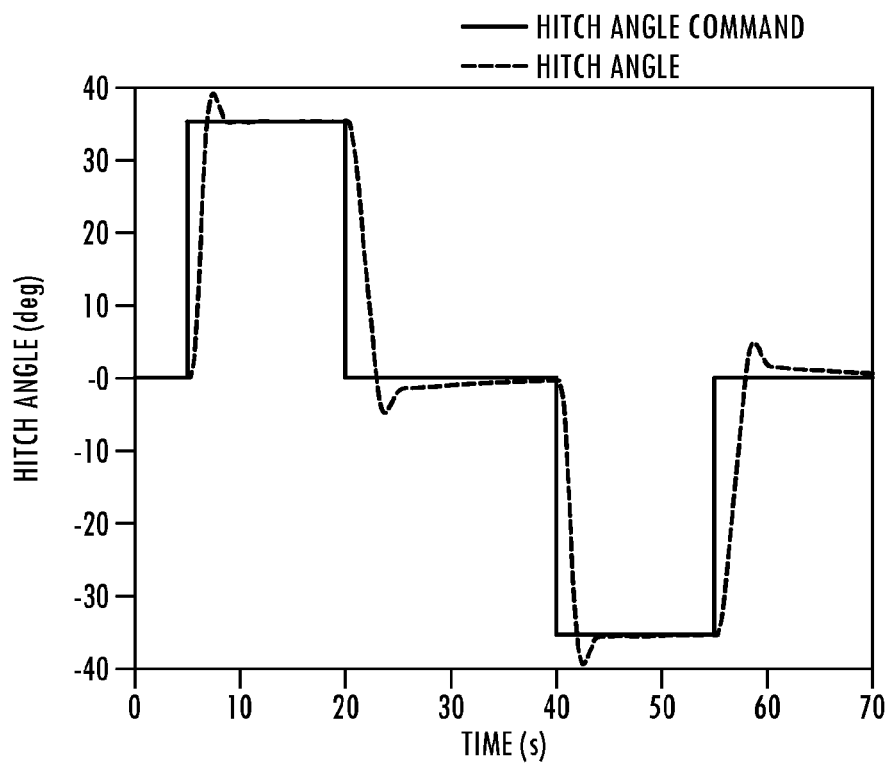
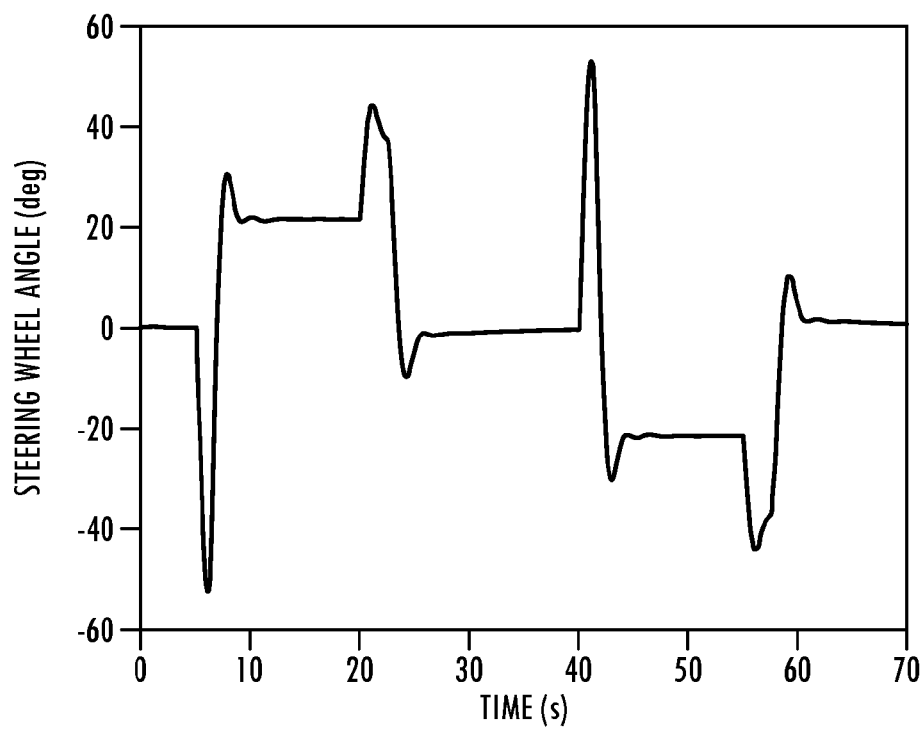
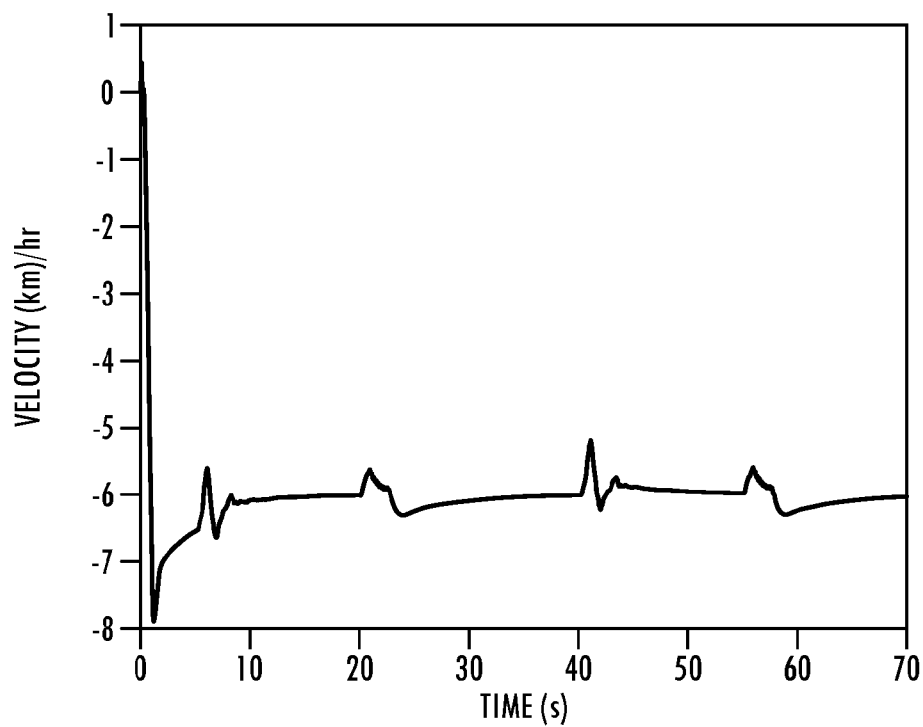


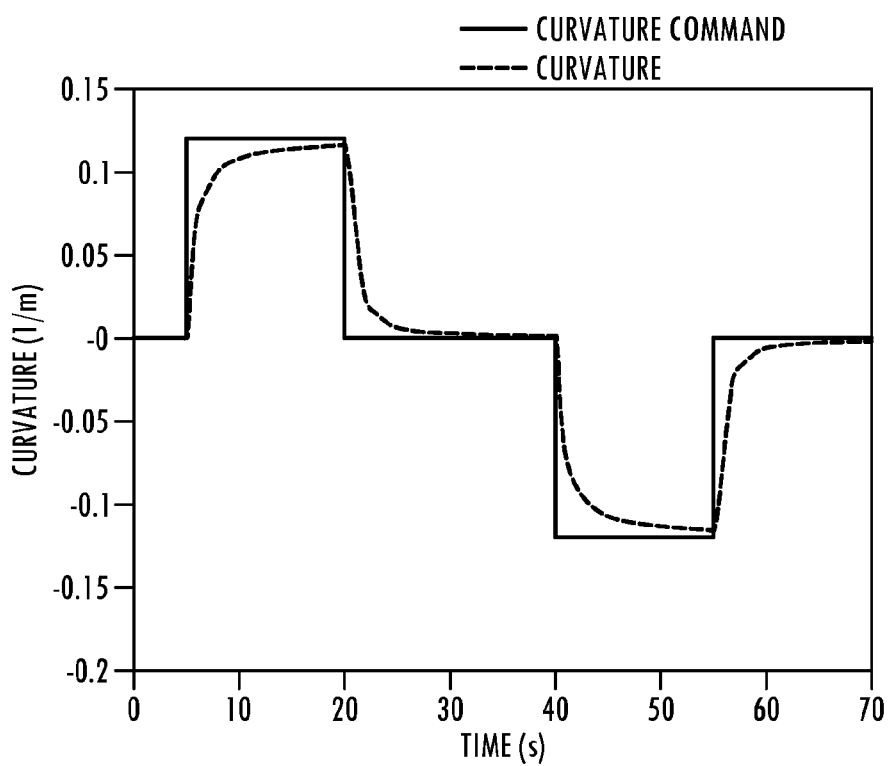
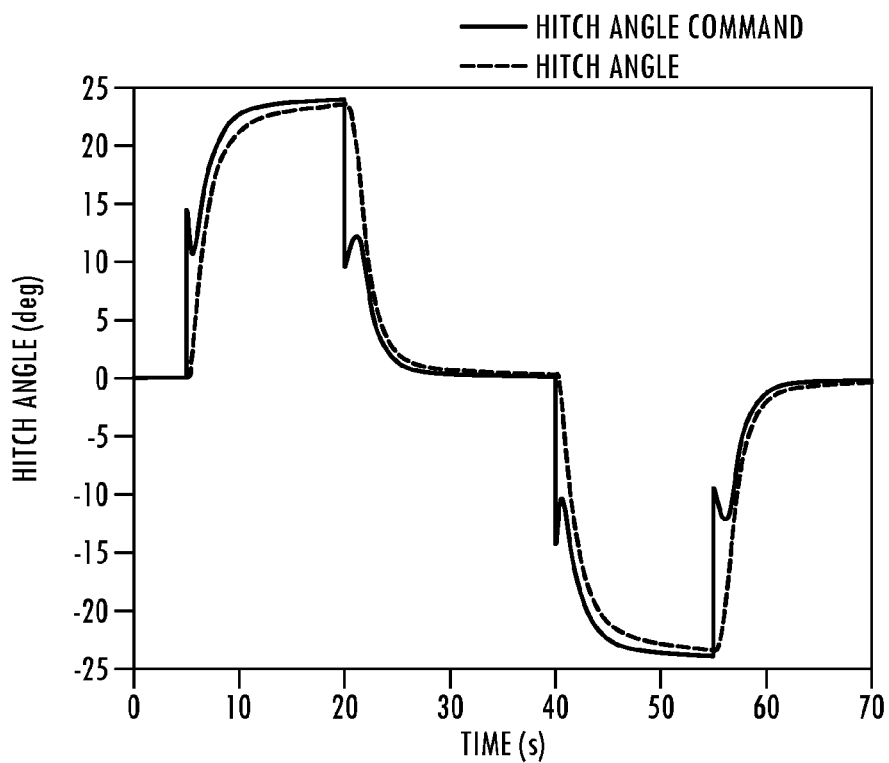
FIG. 60B

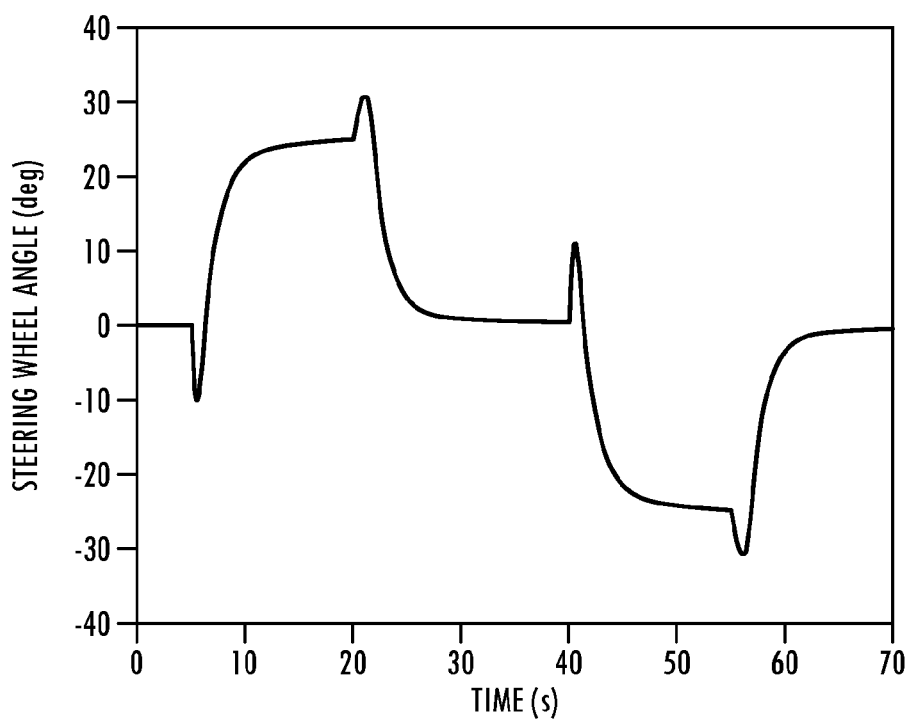
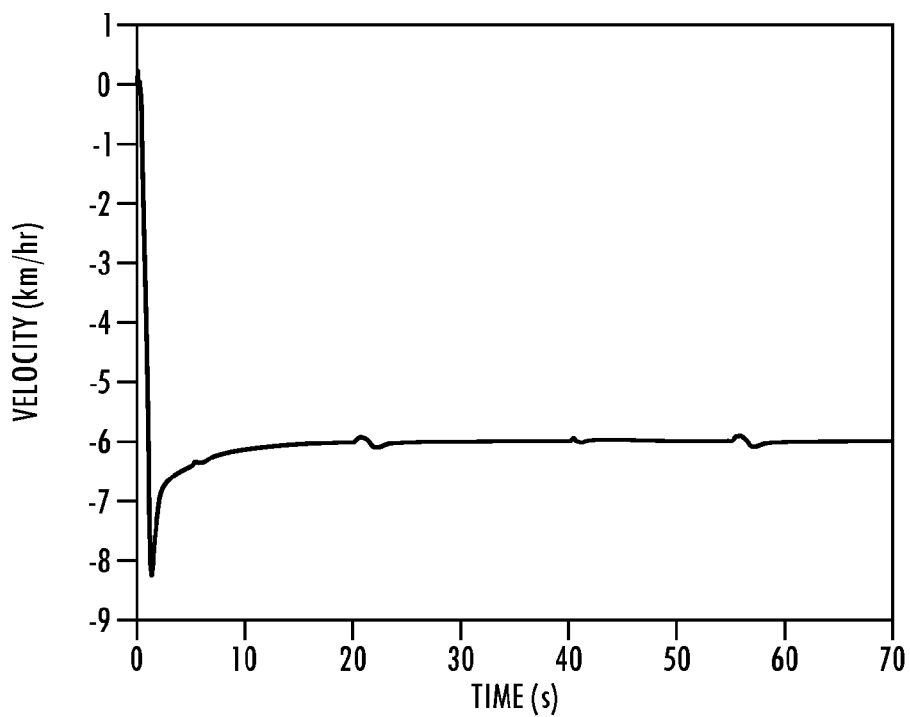


**FIG. 60C**



**FIG. 60D**

**FIG. 61A****FIG. 61B**

**FIG. 61C****FIG. 61D**

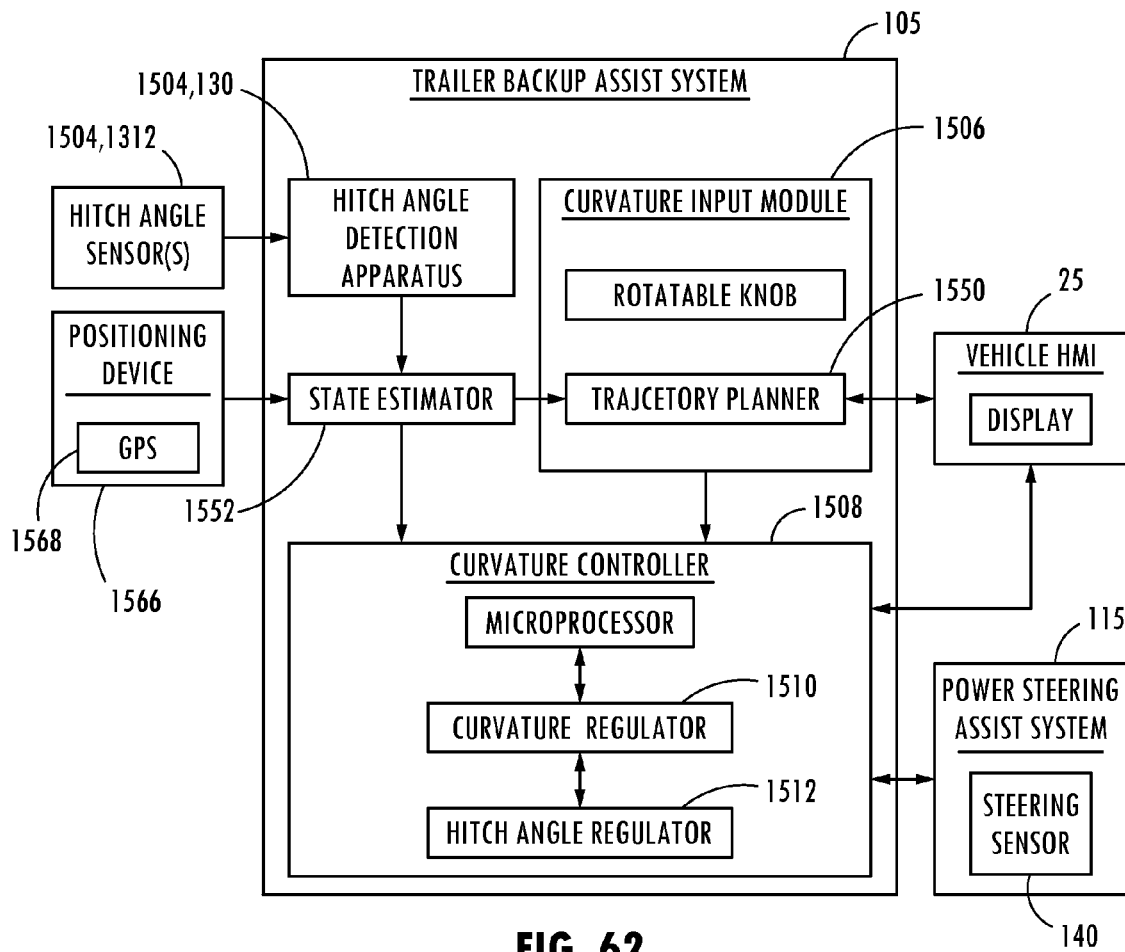


FIG. 62

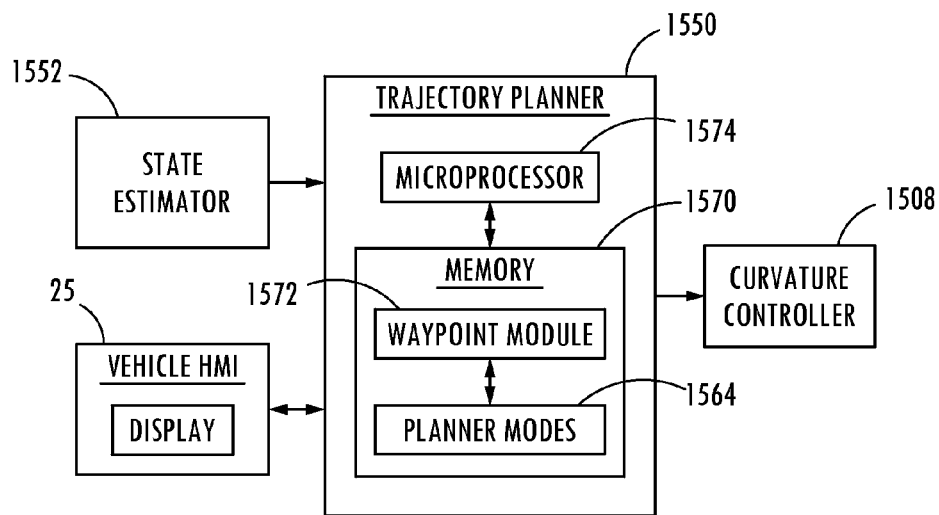


FIG. 63

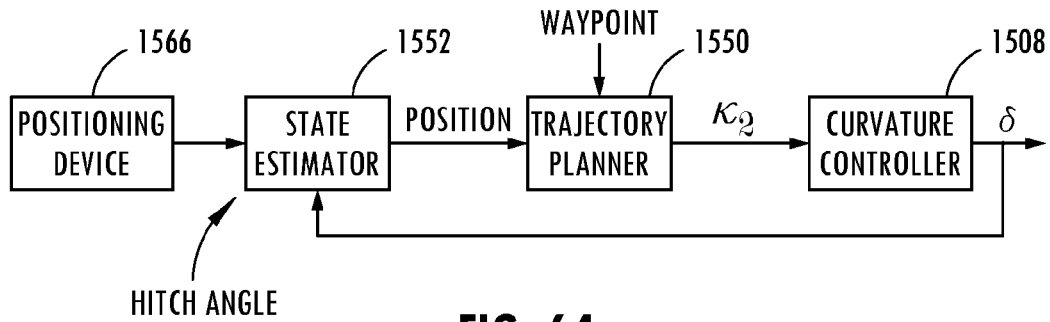


FIG. 64

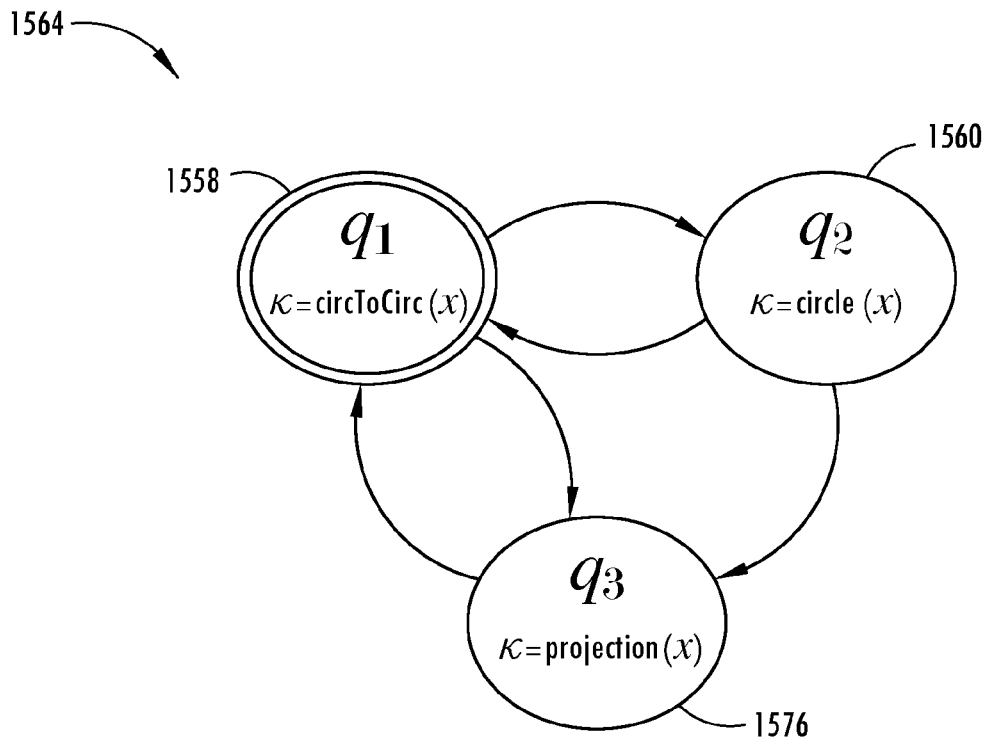


FIG. 65

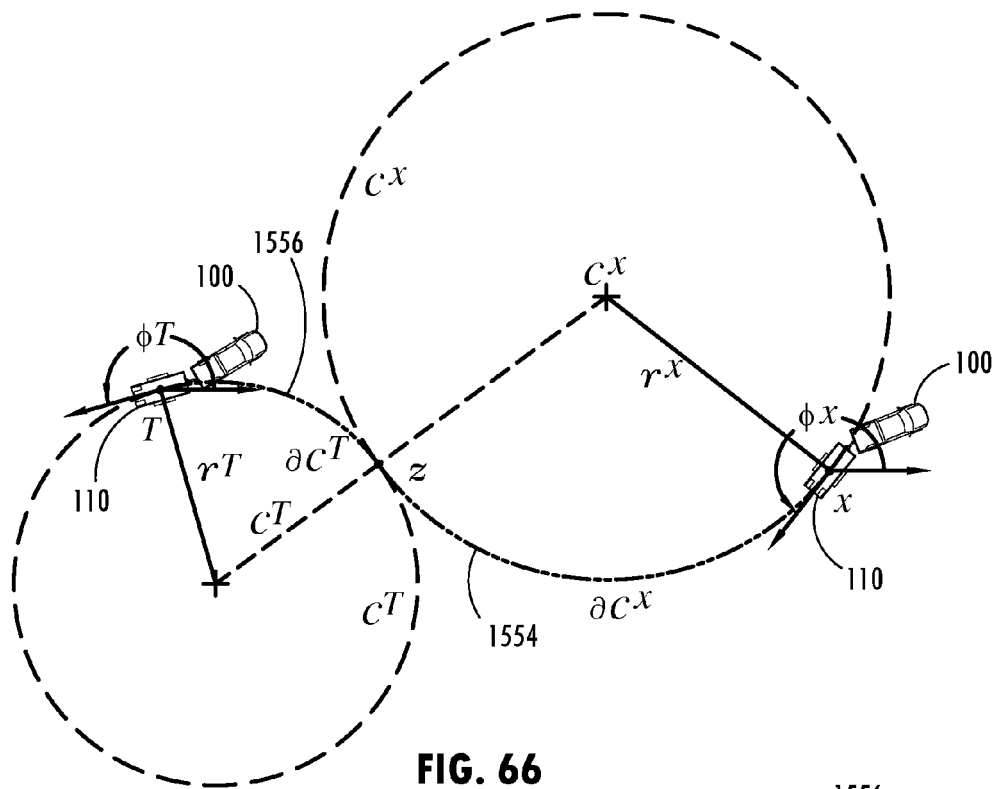


FIG. 66

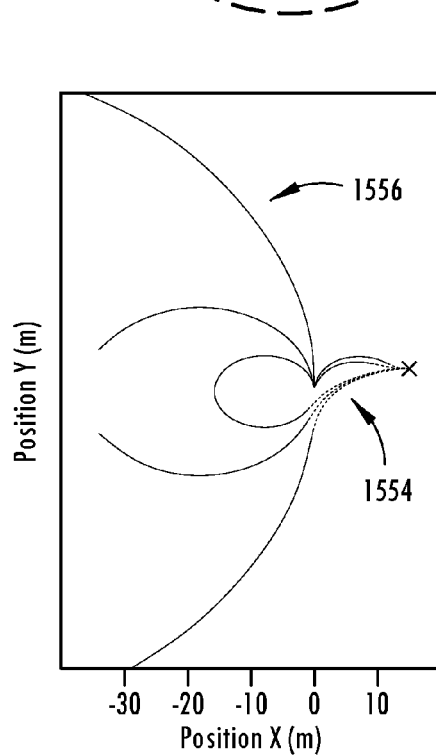
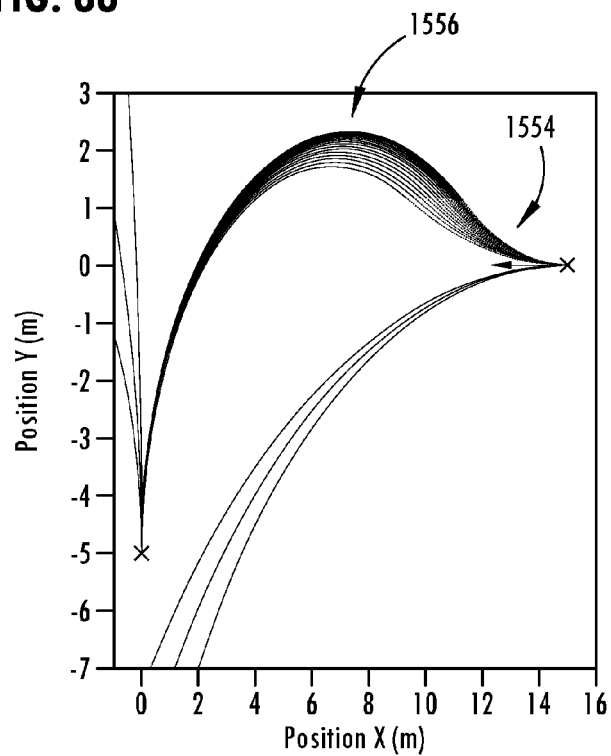


FIG. 67A



**FIG. 67B**



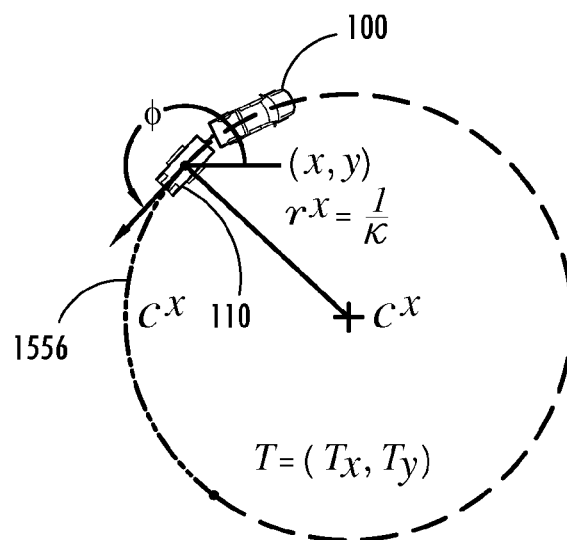


FIG. 68

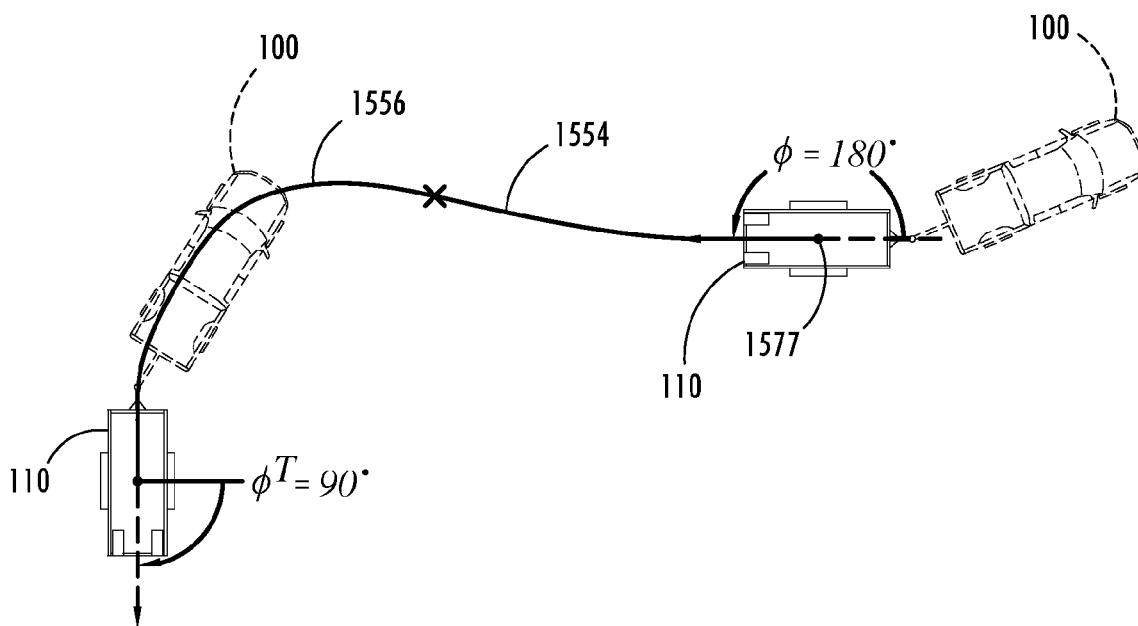


FIG. 69

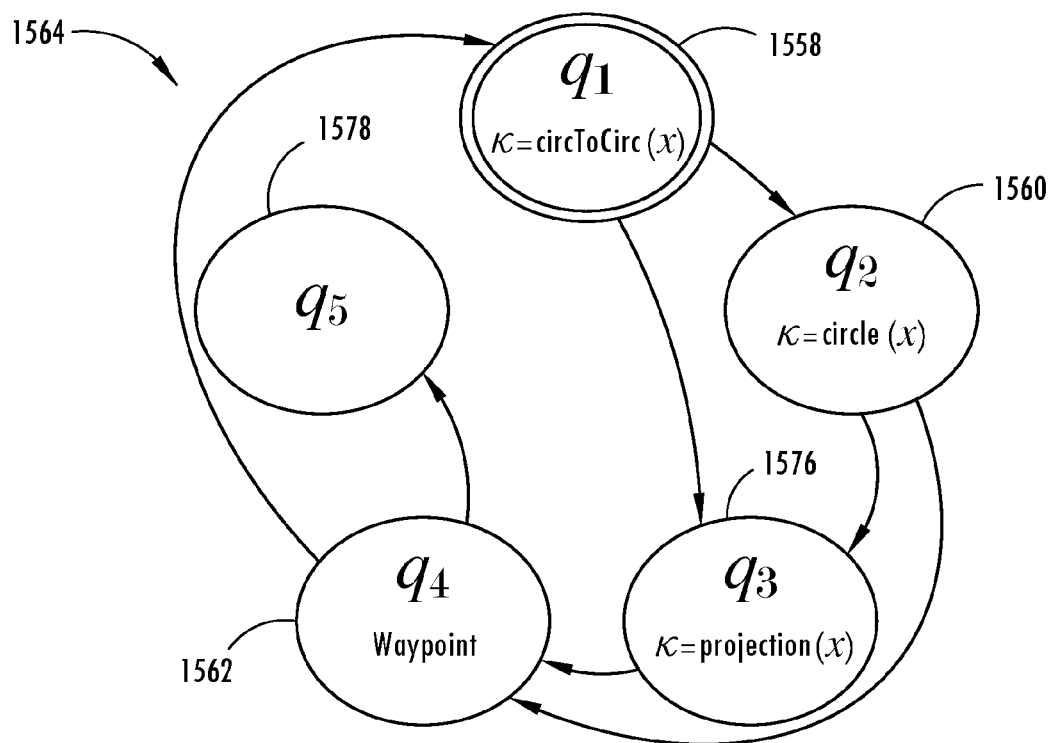


FIG. 70

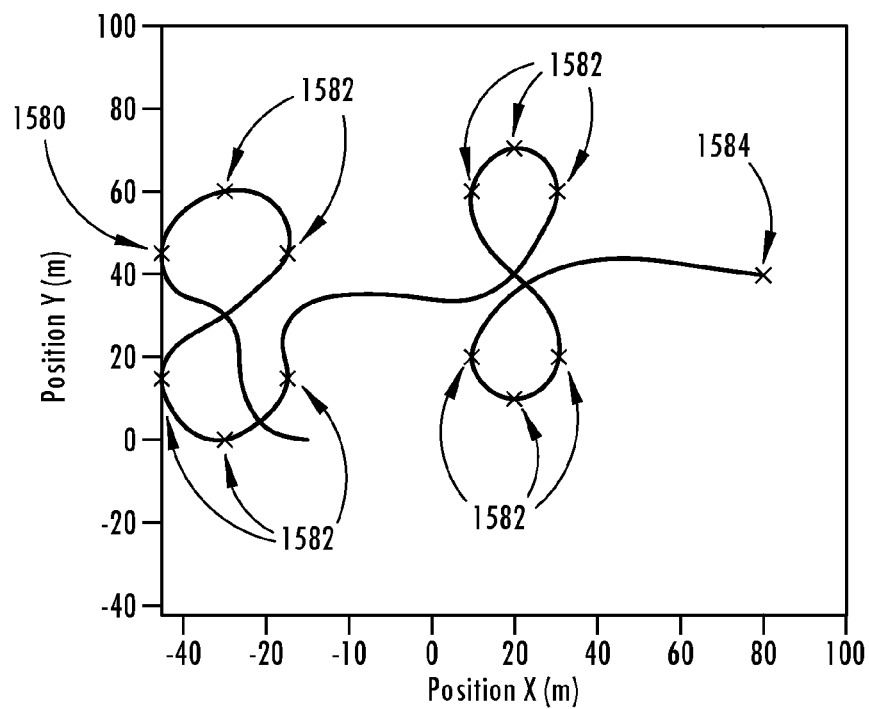


FIG. 71

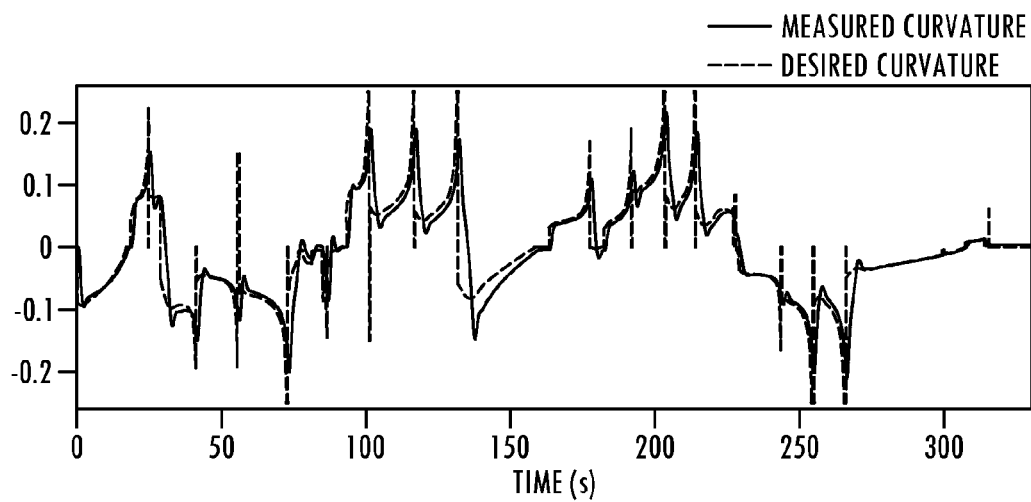


FIG. 72A

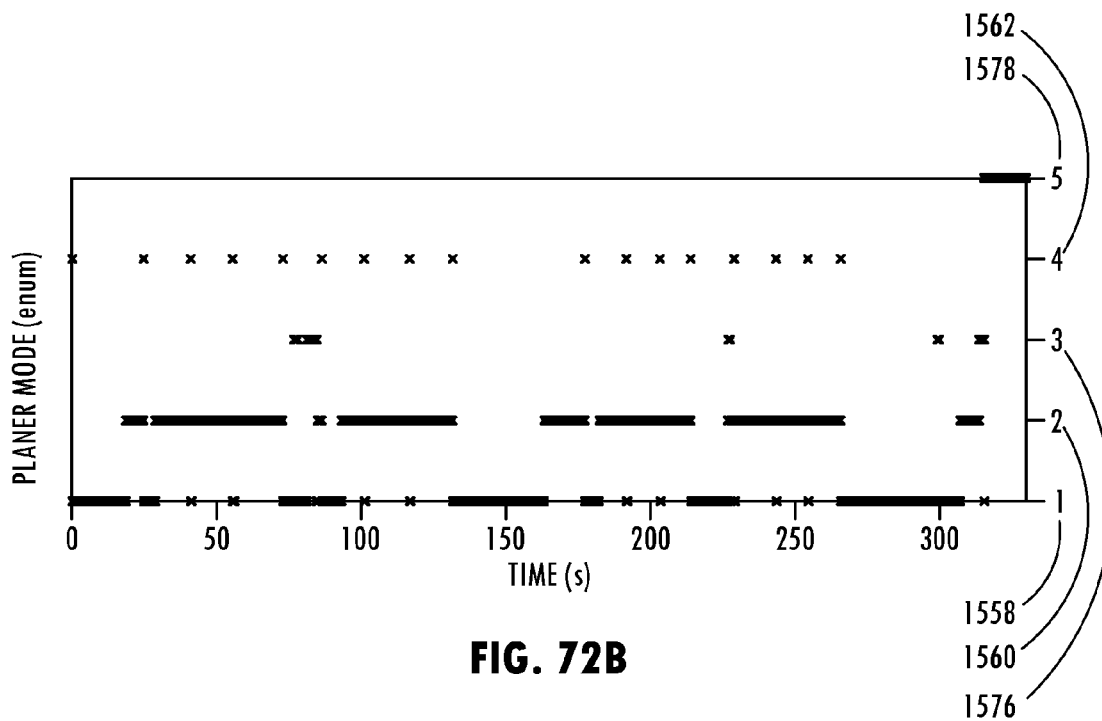


FIG. 72B

# TRAILER BACKUP ASSIST SYSTEM WITH TRAJECTORY PLANNER FOR MULTIPLE WAYPOINTS

## CROSS-REFERENCE TO RELATED APPLICATIONS

This patent application is continuation-in-part of U.S. patent application Ser. No. 14/256,427, which was filed on Apr. 18, 2014, entitled "CONTROL FOR TRAILER BACKUP ASSIST SYSTEM," which is a continuation in part of U.S. patent application Ser. No. 14/249,781, which was filed on Apr. 10, 2014, entitled "SYSTEM AND METHOD FOR CALCULATING A HORIZONTAL CAMERA TO TARGET DISTANCE," which is a continuation-in-part of U.S. patent application Ser. No. 14/188,213, which was filed on Feb. 24, 2014, entitled "SENSOR SYSTEM AND METHOD FOR MONITORING TRAILER HITCH ANGLE," which is a continuation-in-part of U.S. patent application Ser. No. 13/847,508, which was filed on Mar. 20, 2013, entitled "HITCH ANGLE ESTIMATION." U.S. patent application Ser. No. 14/188,213 is also a continuation-in-part of U.S. patent application Ser. No. 14/068,387, which was filed on Oct. 31, 2013, entitled "TRAILER MONITORING SYSTEM AND METHOD," which is a continuation-in-part of U.S. patent application Ser. No. 14/059,835, which was filed on Oct. 22, 2013, entitled "TRAILER BACKUP ASSIST SYSTEM," which is a continuation-in-part of U.S. patent application Ser. No. 13/443,743 which was filed on Apr. 10, 2012, entitled "DETECTION OF AND COUNTER-MEASURES FOR JACKKNIFE ENABLING CONDITIONS DURING TRAILER BACKUP ASSIST," which is a continuation-in-part of U.S. patent application Ser. No. 13/336,060, which was filed on Dec. 23, 2011, entitled "TRAILER PATH CURVATURE CONTROL FOR TRAILER BACKUP ASSIST," which claims benefit from U.S. Provisional Patent Application No. 61/477,132, which was filed on Apr. 19, 2011, entitled "TRAILER BACKUP ASSIST CURVATURE CONTROL." U.S. patent application Ser. No. 14/249,781 is also a continuation-in-part of U.S. patent application Ser. No. 14/161,832 which was filed Jan. 23, 2014, entitled "SUPPLEMENTAL VEHICLE LIGHTING SYSTEM FOR VISION BASED TARGET DETECTION," which is a continuation-in-part of U.S. patent application Ser. No. 14/059,835 which was filed on Oct. 22, 2013, entitled "TRAILER BACKUP ASSIST SYSTEM." Furthermore, U.S. patent application Ser. No. 14/249,781 is a continuation-in-part of U.S. application Ser. No. 14/201,130 which was filed on Mar. 7, 2014, entitled "SYSTEM AND METHOD OF CALIBRATING A TRAILER BACKUP ASSIST SYSTEM," which is a continuation-in-part of U.S. patent application Ser. No. 14/068,387, which was filed on Oct. 31, 2013, entitled "TRAILER MONITORING SYSTEM AND METHOD." The aforementioned related applications are hereby incorporated by reference in their entirety.

## FIELD OF THE INVENTION

The disclosure made herein relates generally to driver assist and active safety technologies in vehicles, and more particularly to a trailer backup assist system that has a trajectory planner configured with a controller to guide a trailer to at least one waypoint position.

## BACKGROUND OF THE INVENTION

Reversing a vehicle while towing a trailer is very challenging for many drivers. This is particularly true for drivers that

are unskilled at backing vehicles with attached trailers, which may include those that drive with a trailer on an infrequent basis (e.g., have rented a trailer, use a personal trailer on an infrequent basis, etc.). One reason for such difficulty is that backing a vehicle with an attached trailer requires steering inputs that are opposite to normal steering when backing the vehicle without a trailer attached and/or requires braking to stabilize the vehicle-trailer combination before a jackknife condition occurs. Another reason for such difficulty is that small errors in steering while backing a vehicle with an attached trailer are amplified thereby causing the trailer to depart from a desired path.

To assist the driver in steering a vehicle with a trailer attached, a trailer backup assist system needs to know the driver's intention. One common assumption with known trailer backup assist systems is that a driver of a vehicle with an attached trailer wants to backup straight and the system either implicitly or explicitly assumes a zero curvature path for the vehicle-trailer combination. Unfortunately most of the real-world use cases of backing a trailer involve a curved path and, thus, assuming a path of zero curvature would significantly limit usefulness of the system.

Another reason backing a trailer can prove to be difficult is the need to control the vehicle in a manner that limits the potential for a jackknife condition to occur. A trailer has attained a jackknife condition when a hitch angle cannot be reduced (i.e., made less acute) while continuously backing up a trailer by application of a maximum steering input for the vehicle such as, for example, by moving steered front wheels of the vehicle to a maximum steered angle at a maximum rate of steering angle change. In the case of the jackknife angle being achieved, the vehicle must be pulled forward to relieve the hitch angle in order to eliminate the jackknife condition and, thus, allow the hitch angle to be controlled via manipulation of the steered wheels of the vehicle. However, in addition to the jackknife condition creating the inconvenient situation where the vehicle must be pulled forward, it can also lead to damage to the vehicle and/or trailer if certain operating conditions of the vehicle relating to its speed, engine torque, acceleration, and the like are not detected and counteracted. For example, if the vehicle is travelling at a suitably high speed in reverse and/or subjected to a suitably high longitudinal acceleration when the jackknife condition is achieved, the relative movement of the vehicle with respect to the trailer can lead to contact between the vehicle and trailer thereby damaging the trailer and/or the vehicle.

## SUMMARY OF THE INVENTION

According to one aspect of the present invention, a trailer backup assist system includes a state estimator determining a current position of a trailer relative to a plurality of waypoints. The trailer backup assist system also includes a trajectory planner for incrementally generating a path from the current position to the plurality of waypoints. The trajectory planner has a first mode that generates first and second circular trajectories tangent to one another connecting between the current position and a waypoint of the plurality of waypoints. A second mode of the trajectory planner generates the second circular trajectory between the current position and the waypoint after the trailer traverses the first circular trajectory. Also, a third mode of the trajectory planner switches to the first operating mode when the trailer reaches the waypoint for guidance to a subsequent waypoint of the plurality of waypoints. The trailer backup assist system further provides a curvature controller guiding the trailer based on a curvature of the respective first or second circular trajectories.

According to another aspect of the present invention, a trajectory planner for a trailer backup assist system includes a first mode that generates a pair of circular trajectories tangent to one another connecting between a current position of a trailer and a waypoint of a plurality of waypoints. The trajectory planner also includes a second mode that generates the second circular trajectory to the waypoint. Further, the trajectory planner includes a third mode that switches to the first operating mode at the waypoint if the plurality of waypoints includes a subsequent waypoint.

According to a further aspect of the present invention, a method is provided for reversing a trailer between a plurality of waypoints. The method provides a step of generating first and second circular trajectories tangent to one another connecting between a current position of the trailer and a first waypoint of the plurality of waypoints. The method also provides a step of guiding the trailer along the first circular trajectory while regenerating the first and second circular trajectories. In addition, the method provides a step of guiding the trailer along the second circular trajectory to the first waypoint while regenerating the second circular trajectory. Further, the method provides a step of generating third and fourth circular trajectories tangent to one another connecting between the current position and a second waypoint of the plurality of waypoints. The method additionally provides a step of guiding the trailer along the third circular trajectory while regenerating the third and fourth circular trajectories. Also, the method provides a step of guiding the trailer along the fourth circular trajectory to the second waypoint.

These and other aspects, objects, and features of the present invention will be understood and appreciated by those skilled in the art upon studying the following specification, claims, and appended drawings.

#### BRIEF DESCRIPTION OF THE DRAWINGS

In the drawings:

FIG. 1 shows a vehicle-trailer combination, the vehicle being configured for performing trailer backup assist functionality in accordance with an embodiment;

FIG. 2 shows one embodiment of the trailer backup steering input apparatus discussed in reference to FIG. 1;

FIG. 3 shows an example of a trailer backup sequence implemented using the trailer backup steering input apparatus discussed in reference to FIG. 2;

FIG. 4 shows a method for implementing trailer backup assist functionality in accordance with an embodiment;

FIG. 5 is a diagrammatic view showing a kinematic model configured for providing information utilized in providing trailer backup assist functionality in accordance with one embodiment;

FIG. 6 is a graph showing an example of a trailer path curvature function plot for a rotary-type trailer backup steering input apparatus configured in accordance with the disclosed subject matter;

FIG. 7 is a diagrammatic view showing a relationship between hitch angle and steered angle as it relates to determining a jackknife angle for a vehicle/trailer system in reverse or backing up;

FIG. 8 shows a method for implementing jackknife countermeasures functionality in accordance with an embodiment;

FIG. 9 shows a human machine interface (HMI) device associated with the trailer backup assist;

FIG. 10 shows a flow diagram associated with the trailer backup assist;

FIG. 11 shows a flow diagram of the setup module according to one embodiment;

FIG. 12 shows an example of an image displayed at the HMI device in accordance with one embodiment;

FIG. 13 is a block diagram illustrating the vehicle trailer backup assist system employing a target monitor controller, according to one embodiment;

FIG. 14 is a schematic diagram illustrating user placement of the target on a trailer towed by a vehicle;

FIG. 15 is an enlarged view of the front portion of the trailer further illustrating the target placement zone in relation to the target sticker;

FIG. 16 is a front view of a portable device having a display illustrating the overlay of a target onto a target placement zone on the trailer;

FIG. 17 is a flow diagram illustrating a method of assisting a user with the placement of the target on the trailer;

FIG. 18 is a flow diagram illustrating a method of monitoring placement of the target on the trailer and generating feedback alert;

FIG. 19 is a schematic view of a front portion of the trailer having a target mounting system assembled thereto, according to one embodiment;

FIG. 20 is an exploded view of the target mounting system and trailer shown in FIG. 19;

FIG. 21 is a flow diagram illustrating an initial set up routine for monitoring the trailer connection for target changes and resetting trailer selection;

FIG. 22 is a flow diagram illustrating a target moved detection routine for monitoring presence of trailer changes and resetting trailer selection;

FIG. 23A is an image of the trailer showing the target in a first position;

FIG. 23B is an image of the trailer showing movement of the target to a second position, according to one example;

FIG. 24 is a flow diagram illustrating a trailer connection monitoring routine for monitoring trailer disconnection;

FIG. 25A is an image of a tow vehicle showing a keylock hole defined in a tailgate handle assembly of the tow vehicle;

FIG. 25B is an enlarged partial rear perspective view of a tailgate handle assembly defining a keylock hole;

FIG. 25C is an enlarged partial front perspective view of the tailgate handle assembly showing the customary use of a keylock cylinder with the keylock hole;

FIG. 25D shows the keylock cylinder mounted to the tailgate handle, according to one embodiment;

FIG. 26A is a front perspective view of a light assembly, according to one embodiment;

FIG. 26B is a rear perspective view of the light assembly;

FIG. 26C is an exploded view of the light assembly shown in FIGS. 26A and 26B;

FIG. 26D is a cross sectional view of the light assembly taken along line XXVI D-XXVI D of FIG. 26A;

FIG. 27A is a light assembly mounted to the tailgate handle assembly shown in FIG. 25B, according to one embodiment;

FIG. 27B is an enlarged partial front perspective view of the tailgate handle assembly equipped with the light assembly shown in FIG. 27A;

FIG. 28 is a schematic diagram illustrating a supplemental vehicle lighting system being implemented in the tow vehicle shown in FIG. 25A, wherein the tow vehicle is attached to a trailer and features a trailer backup assist system employing vision based target detection;

FIG. 29 is a top plan view of a trailer attached to a vehicle having a sensor system, according to one embodiment;

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FIG. 30 is a block diagram illustrating the trailer backup assist system employing a sensor system that has a primary sensor and a secondary sensor, according to one embodiment;

FIG. 31 is a flow diagram illustrating a method for estimating an actual hitch angle of a trailer attached to a vehicle with a sensor system;

FIG. 32 is an automotive vehicle having a hitch angle estimating system of the disclosed subject matter;

FIG. 33 is a block diagram of a vehicle having a trailer coupled thereto and a relationship to the law of cosines;

FIG. 34 is a flow chart of a method of estimating a hitch angle;

FIG. 35 is a block diagram illustrating one embodiment of the trailer backup assist system having the trailer backup assist control module with a hitch angle calibration routine;

FIG. 36 is a diagram that illustrates the geometry of a vehicle and a trailer overlaid with a two-dimensional x-y coordinate system that identifies variables used to calculate kinematic information of the vehicle and trailer system;

FIG. 37 is a flow diagram illustrating one embodiment of the hitch angle calibration routine;

FIG. 38 is a flow diagram illustrating an initiating routine that is preformed prior to calculating the trailer angle offset, according to one embodiment;

FIG. 39 is a flow diagram illustrating an additional embodiment of the hitch angle calibration routine;

FIG. 40 is a flow diagram illustrating a method of calibrating a trailer backup assist system before determining an offset of the measured hitch angle;

FIG. 41 is a rear perspective view of a vehicle and a trailer having a hitch angle sensor assembly according to one embodiment;

FIG. 42 is an enlarged perspective view taken from section 42 of FIG. 41, showing one embodiment of the hitch angle sensor assembly coupled between the vehicle and the trailer;

FIG. 42A is a bottom perspective view of the hitch angle sensor assembly, as shown in FIG. 42;

FIG. 43 is a top perspective view of the hitch angle sensor assembly of FIG. 42;

FIG. 44 is an exploded top perspective view of the hitch angle sensor assembly of FIG. 42;

FIG. 45 is a top plan view of the hitch angle sensor assembly, showing the vehicle and the trailer in a straight line configuration, according to one embodiment;

FIG. 46 is a top plan view of the hitch angle sensor assembly, showing the trailer articulated to a first hitch angle, according to one embodiment;

FIG. 47 is a top plan view of the hitch angle sensor assembly, showing the trailer articulated to a second hitch angle, according to one embodiment;

FIG. 48 is a block diagram illustrating one embodiment of the trailer backup assist system having a camera based target detection system;

FIG. 49 is a top perspective view of a vehicle attached to a trailer, the vehicle having a rear camera with a vertical field of view for imaging a target disposed on the trailer;

FIG. 50 is a diagram that illustrates a vehicle and a trailer accompanied by the geometry and variables used to calculate a horizontal camera to target distance;

FIG. 51 is a diagram that illustrates certain aspects of the geometry and variables used to calculate the horizontal camera to target distance;

FIG. 52 is a diagram illustrating a vehicle and a trailer, the trailer having a draw bar with a drop;

FIG. 53 is a diagram illustrating an image taken from a rear camera showing a target disposed on a trailer;

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FIG. 54 is a side elevation view of a gooseneck trailer coupled with a vehicle, according to one embodiment;

FIG. 55 is a block diagram illustrating one embodiment of the trailer backup assist system having a controller for generating a steering angle command;

FIG. 56 is a schematic diagram illustrating one embodiment of a rotational control input device for selecting a desired curvature of a trailer and a corresponding top plan view of a vehicle and a trailer with the various trailer curvature paths correlating with desired curvatures that may be selected;

FIG. 57 is a schematic block diagram illustrating portions of the controller of FIG. 55 and other components of the trailer backup assist system, according to one embodiment;

FIG. 58 is a schematic block diagram of the controller of FIG. 55, showing the feedback architecture and signal flow of the controller, according to one embodiment;

FIG. 59 is a flow diagram illustrating a method of operating a trailer backup assist system, according to one embodiment;

FIGS. 60A-D are plotted graphs of system variables in simulating operation of the trailer backup assist system of FIG. 55 with a gooseneck trailer;

FIGS. 61A-D are plotted graphs of system variables in simulating operation of the trailer backup assist system of FIG. 55 with a conventional trailer;

FIG. 62 is a block diagram illustrating one embodiment of the trailer backup assist system having a trajectory planner providing a desired curvature to a curvature controller;

FIG. 63 is a block diagram illustrating one embodiment of the trajectory planner having a memory with a waypoint module and planner modes;

FIG. 64 is a schematic block diagram of the control system of FIG. 62, showing the feedback architecture and signal flow, according to one embodiment;

FIG. 65 is a flow diagram of planner modes, according to one embodiment;

FIG. 66 is a schematic top plan view of first and second circular trajectories generated with the trajectory planner, according to one embodiment;

FIGS. 67A-B are graphs of a coordinate system with various first and second circular trajectories plotted between different embodiments of a current position and a waypoint position;

FIG. 68 is schematic top plan view of the second circular trajectory generated with the trajectory planner, according to one embodiment;

FIG. 69 is a schematic top plan view of one embodiment of a path traveled by a trailer with a vehicle using the trailer backup assist system of FIG. 62;

FIG. 70 is a flow diagram of planner modes, according to an additional embodiment;

FIG. 71 is a graph of a coordinate system with a simulated path of a trailer traveled between various waypoints using the trailer backup assist system, according to one embodiment;

FIG. 72A is a plotted graph of desired curvature and measured curvature in simulating operation of the trailer backup assist system of FIG. 71; and

FIG. 72B is a plotted graph of the planner modes used in simulating operation of the trailer backup assist system of FIG. 71.

#### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

While various aspects of the inventive subject matter are described with reference to a particular illustrative embodiment, the inventive subject matter is not limited to such

embodiments, and additional modifications, applications, and embodiments may be implemented without departing from the inventive subject matter. In the figures, like reference numbers will be used to illustrate the same components. Those skilled in the art will recognize that the various components set forth herein may be altered without varying from the scope of the inventive subject matter.

The disclosed subject matter is directed to providing trailer backup assist functionality in a manner that is relatively low cost and that offers an intuitive user interface. In particular, such trailer backup assist functionality provides for controlling curvature of a path of travel of a trailer attached to a vehicle (i.e., trailer path curvature control) by allowing a driver of the vehicle to specify a desired path of the trailer by inputting a desired trailer path curvature as the backup maneuver of the vehicle and trailer progresses. Although a control knob, a set of virtual buttons, or a touch screen can each be implemented for enabling trailer path curvature control, the disclosed subject matter is not unnecessarily limited to any particular configuration of interface through which a desired trailer path curvature is inputted. Furthermore, in the case where a steering wheel can be mechanically decoupled from steered wheels of the vehicle, the steering wheel can also be used as an interface through which a desired trailer path curvature is inputted. As will be discussed herein in greater detail, kinematical information of a system defined by the vehicle and the trailer are used to calculate a relationship (i.e., kinematics) between the trailer's curvature and the steering angle of the vehicle for determining steering angle changes of the vehicle for achieving the specified trailer path. Steering commands corresponding to the steering angle changes are used for controlling a steering system of the tow vehicle (e.g., electric power assisted steering (EPAS) system) for implementing steering angle changes of steered wheels of the vehicle to achieve (e.g., to approximate) the specified path of travel of the trailer. The trailer backup assist system automatically steers the vehicle-trailer combination as a driver uses the vehicle transmission, accelerator and brake to reverse the vehicle-trailer combination. The driver inputs a desired trailer curvature command by using an input device such as a trailer steering knob.

Trailer backup assist functionality may be directed to implementing one or more countermeasures for limiting the potential of a jackknife condition being attained between a vehicle and a trailer being towed by the vehicle while backing up. In certain embodiments, curvature of a path of travel of the trailer (i.e., trailer path curvature control) can be controlled by allowing a driver of the vehicle to specify a desired path of the trailer by inputting a desired trailer path curvature as the backup maneuver of the vehicle and trailer progresses. Although a control knob, a set of virtual buttons, or a touch screen can each be implemented for enabling trailer path curvature control, the disclosed subject matter is not unnecessarily limited to any particular configuration of interface through which a desired trailer path curvature is inputted. Furthermore, in the case where a steering wheel can be mechanically decoupled from steered wheels of the vehicle, the steering wheel can also be used as an interface through which a desired trailer path curvature is inputted. As will be discussed herein in greater detail, kinematic information of a system defined by the vehicle and the trailer are used to calculate a relationship (i.e., kinematics) between the trailer's curvature and the steering angle of the vehicle for determining steering angle changes of the vehicle for achieving the specified trailer path. Steering commands corresponding to the steering angle changes are used for controlling a steering system of the tow vehicle (e.g., electric power assisted steer-

ing (EPAS) system) for implementing steering angle changes of steered wheels of the vehicle to achieve (e.g., to approximate) the specified path of travel of the trailer.

Embodiments of the disclosed subject matter are directed to trailer backup assist functionality that provides for a user interface for a system that controls curvature of a path of a trailer being backed by a vehicle. More specifically, trailer backup assist functionality configured in accordance with embodiments of the disclosed subject matter provide for such trailer path curvature control by allowing a driver of the vehicle to specify a desired path of the trailer by inputting a desired trailer path curvature as the backup maneuver of the vehicle and trailer progresses. In response to such path of the trailer being specified by the driver, embodiments of the disclosed subject matter control a power assisted steering system (e.g., electric power assisted steering (EPAS) system) of the vehicle for implementing steering angle changes of steered wheels of the vehicle to achieve the specified trailer path. Kinematics of the vehicle and the trailer are used to determine the steering angle changes that are required for achieving the specified trailer path. Accordingly, embodiments of the disclosed subject matter provide for implementation of trailer backup assist functionality in a manner that is relatively simple and that enables use of an intuitive vehicle operator interface for specifying trailer path curvature control.

The disclosed subject matter, furthermore, includes embodiments directed to determining a hitch angle of trailer attached to the vehicle. In one such embodiment, the vehicle trailer backup assist system may utilize a target placed on the trailer, allowing the trailer backup assist system to employ information acquired via image acquisition and processing of the target. According to other embodiments, the target may be used to identify if a connected trailer has changed, trailer connection or disconnection, and other trailer related information. The target is an identifiable visual target that can be captured in an image by the video imaging camera and detected and processed via image processing. According to one embodiment, the target may be attached to the trailer, preferably within a target placement zone, such that the camera and image processing may detect the target and its location on the trailer to determine trailer related information, such as the hitch angle between the trailer and the towing vehicle. The trailer backup assist system may provide to the user one or more image(s) of the trailer target zone for proper placement of the target to assist with placement of the target on the trailer. Additionally, the vehicle trailer backup assist system may monitor the target to determine if the target has been correctly placed within a desired target placement zone and provide feedback alert(s) to the user. Further, the trailer backup assist system may monitor the trailer connection by monitoring the target to determine if the target has moved to determine whether the same trailer remains connected to the tow vehicle, and may initiate action in response thereto. Further, the trailer backup assist system may monitor the hitch angle or the target to determine if the trailer may have been changed out (i.e., disconnected and replaced with another trailer), and may initiate action in response thereto.

The disclosed subject matter also provides a supplemental vehicle lighting system that is responsive to a trailer backup assist system. The system includes a rear vehicle fixture defining a keylock hole customarily used in conjunction with a corresponding keylock cylinder. A light assembly is provided in the place of a keylock cylinder and operably coupled to the keylock hole. The light assembly includes a housing having a barrel that is concentrically aligned with the keylock hole and includes a distal end and a proximal end. A lighting device is disposed inside the housing and operable to emit

light through the barrel beginning from the proximal end. A lens is coupled to the distal end of the barrel and is disposed to at least partially coincide with the keylock hole, wherein the lens is configured to disperse light emitted from the lighting device to illuminate a rear vehicle area.

In some embodiments of the disclosed trailer backup assist system, it can be advantageous to use information that is representative of a hitch angle between the vehicle and a trailer attached to the vehicle. The disclosed subject matter provides embodiments directed to estimating an actual hitch angle of a trailer attached to a vehicle, as in some situations sensor information may become unavailable or may otherwise not provide an accurate measurement of the hitch angle. A hitch angle that is not accurate may introduce a potential for inadequate or improper vehicle system control, especially when the hitch angle information is important to controlling the vehicle system, such as a trailer backup assist system or a trailer brake controller. According to one embodiment, a sensor system for estimating an actual hitch angle of a trailer attached to a vehicle includes a primary sensor having a camera monitoring a target on the trailer to determine a measured hitch angle and a secondary sensor that monitors the trailer to determine an indicator of the actual hitch angle. The trailer backup assist system may then operate the vehicle when the measured hitch angle correlates with the indicator of the actual hitch angle, confirming that the measured hitch angle is a generally accurate estimate of the actual hitch angle.

According to an additional embodiment of the disclosed subject matter, a system for estimating a hitch angle between a vehicle and a trailer coupled thereto has a wireless receiver on the vehicle located a predetermined distance from a trailer mount and a wireless transmitter located at an end of the trailer opposite the trailer mount. According to one embodiment, a controller monitors power returns of a signal transmitted from the transmitter to the receiver and thereby estimates a distance between the transmitter and the receiver as a function of a path loss propagation of the transmitted signal. The hitch angle is then estimated using the estimated distance, the predetermined distance, and a trailer length.

To further ensure the accuracy of the measured hitch angle, in additional embodiments the trailer back assist system may include a hitch angle calibration routine for determining any offset between the measured hitch angle and the actual hitch angle, based on certain vehicle and/or trailer characteristics. In one of these embodiments, a method provides for sensing a measured hitch angle with at least one hitch angle sensor on the vehicle and sensing a steering angle of the steered wheels of the vehicle. The method further provides for reversing the vehicle, and thereby determining an offset between the measured hitch angle and the actual hitch angle when the measured hitch angle and the steering angle are substantially consistent while the vehicle is reversing. Another one of these embodiments provides driving the vehicle forward substantially straight above a threshold speed while sensing a yaw rate of the vehicle and sensing a measured hitch angle of the trailer. Further, the method provides for determining an angle rate based on the measured hitch angle, and then determining an offset between the measured hitch angle and the actual hitch angle when the yaw rate and the angle rate are substantially zero. The offset may then be used to more accurately manipulate the actual hitch angle with the trailer backup assist system.

The disclosed subject matter includes an additional embodiment directed to determine a hitch angle of a trailer attached to a vehicle. In one embodiment, a hitch angle sensor assembly includes a spacer fixed between a hitch ball and a

mounting surface on the vehicle. The hitch angle sensor assembly also provides an element that is rotatably coupled with the spacer about a vertical axis defined by the hitch ball. A connecting member secures the element to the trailer. A magnet is coupled with the element and has an arcuate shape with spacing from the vertical axis that increases between opposing ends thereof. A hall sensor is coupled with the spacer and senses the magnet to determine a rotated position of the element, thereby determining a hitch angle. This and other embodiments of the hitch angle sensor assembly may be used independently or in combination with other hitch angle sensors or systems to estimate the hitch angle between the vehicle and trailer, which may be advantageously used for operation of a vehicle with a trailer backup assist system.

According to an additional embodiment of the disclosed subject matter, a system and method for calculating a horizontal camera to target distance can be used by the trailer backup assist system. In one embodiment, a camera on board a vehicle is configured to image a target on a trailer that is aligned with the vehicle. A controller is in communication with the camera and is supplied a user-obtained measurement. The controller is configured to calculate a first horizontal distance and a second horizontal distance, and to sum the first and second horizontal distances to calculate a horizontal camera to target distance.

In one embodiment of the disclosed subject matter, a trailer backup assist system includes a controller that is configured to operate the trailer backup assist system irrespective of the trailer attached to the vehicle. In the embodiment the trailer backup assist system generally provides a sensor that senses a measured hitch angle between a vehicle and a trailer. The system also provides an input module that receives a desired curvature of the trailer. A controller of the system includes a curvature regulator determining a desired hitch angle based on the desired curvature and a steering angle of the vehicle. In addition, the controller of the system includes a hitch angle regulator generating a steering angle command based on the desired hitch angle and the measured hitch angle, whereby the steering angle command is configured to adjust the steering angle consistent with the desired curvature.

Furthermore, in one embodiment of the disclosed subject matter, a trailer backup assist system includes a state estimator that determines a current position of a trailer relative to a waypoint position. A trajectory planner generates first and second circular trajectories tangent to one another spanning between the current and the waypoint positions. The trailer backup assist system also includes a controller reversing the trailer to the waypoint position along the first and second circular trajectories, which are dynamically regenerated as the trailer reverses along the first circular trajectory. In an additional embodiment that includes multiple waypoints, a trailer backup assist system includes a state estimator determining a current position of a trailer relative to a plurality of waypoints and a trajectory planner incrementally generating a path from the current position to the plurality of waypoints. The trajectory planner in this embodiment includes a first mode generating first and second circular trajectories tangent to one another connecting between the current position and a waypoint of the plurality of waypoints, a second mode generating the second circular trajectory between the current position and the waypoint after the trailer traverses the first circular trajectory, and a third mode switching to the first operating mode when the trailer reaches the waypoint for guidance to a subsequent waypoint of the plurality of waypoints. Similarly, in this embodiment, the trailer backup assist



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system includes a curvature controller that guides the trailer based on a curvature of the respective first or second circular trajectories.

#### Trailer Backup Assist System

Referring to FIG. 1, an embodiment of a vehicle **100** configured for performing trailer backup assist functionality is shown. A trailer backup assist system **105** of the vehicle **100** controls the curvature of path of travel of a trailer **110** that is attached to the vehicle **100**. Such control is accomplished through interaction of a power assisted steering system **115** of the vehicle **100** and the trailer backup assist system **105**. During operation of the trailer backup assist system **105** while the vehicle **100** is being reversed, a driver of the vehicle **100** is sometimes limited in the manner in which he/she can make steering inputs via a steering wheel of the vehicle **100**. This is because in certain vehicles the trailer backup assist system **105** is in control of the power assisted steering system **115** and the power assisted steering system **115** is directly coupled to the steering wheel (i.e., the steering wheel of the vehicle **100** moves in concert with steered wheels of the vehicle **100**). As is discussed below in greater detail, a human machine interface (HMI) device of the backup assist system **105** is used for commanding changes in curvature of a path of the trailer **110** such as a knob, thereby decoupling such commands from being made at the steering wheel of the vehicle **100**. However, some vehicles configured to provide trailer backup assist functionality in accordance with the disclosed subject matter will have the capability to selectively decouple steering movement from movement of steerable wheels of the vehicle, thereby allowing the steering wheel to be used for commanding changes in curvature of a path of a trailer during such trailer backup assist.

The trailer backup assist system **105** includes a trailer backup assist control module **120**, a trailer backup steering input apparatus **125**, and a hitch angle detection apparatus **130**. The trailer backup assist control module **120** is connected to the trailer backup steering input apparatus **125** and the hitch angle detection apparatus **130** for allowing communication of information therebetween. It is disclosed herein that the trailer backup steering input apparatus can be coupled to the trailer backup assist control module **120** in a wired or wireless manner. The trailer backup assist system control module **120** is attached to a power steering assist control module **135** of the power steering assist system **115** for allowing information to be communicated therebetween. A steering angle detection apparatus **140** of the power steering assist system **115** is connected to the power steering assist control module **135** for providing information thereto. The trailer backup assist system is also attached to a brake system control module **145** and a powertrain control module **150** for allowing communication of information therebetween. Jointly, the trailer backup assist system **105**, the power steering assist system **115**, the brake system control module **145**, the powertrain control module **150**, and the gear selection device (PRNDL), define a trailer backup assist architecture configured in accordance with an embodiment.

The trailer backup assist control module **120** is configured for implementing logic (i.e., instructions) for receiving information from the trailer backup steering input apparatus **125**, the hitch angle detection apparatus **130**, the power steering assist control module **135**, the brake system control module **145**, and the powertrain control module **150**. The trailer backup assist control module **120** (e.g., a trailer curvature algorithm thereof) generates vehicle steering information as a function of all or a portion of the information received from the trailer backup steering input apparatus **125**, the hitch angle detection apparatus **130**, the power steering assist con-

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trol module **135**, the brake system control module **145**, and the powertrain control module **150**. Thereafter, the vehicle steering information is provided to the power steering assist control module **135** for affecting steering of the vehicle **100** by the power steering assist system **115** to achieve a commanded path of travel for the trailer **110**.

The trailer backup steering input apparatus **125** provides the trailer backup assist control module **120** with information defining the commanded path of travel of the trailer **110** to the trailer backup assist control module **120** (i.e., trailer steering information). The trailer steering information can include information relating to a commanded change in the path of travel (e.g., a change in radius of path curvature) and information relating to an indication that the trailer is to travel along a path defined by a longitudinal centerline axis of the trailer (i.e., along a substantially straight path of travel). As will be discussed below in detail, the trailer backup steering input apparatus **125** preferably includes a rotational control input device for allowing a driver of the vehicle **100** to interface with the trailer backup steering input apparatus **125** to command desired trailer steering actions (e.g., commanding a desired change in radius of the path of travel of the trailer and/or commanding that the trailer travel along a substantially straight path of travel as defined by a longitudinal centerline axis of the trailer). In a preferred embodiment, the rotational control input device is a knob rotatable about a rotational axis extending through a top surface/face of the knob. In other embodiments, the rotational control input device is a knob rotatable about a rotational axis extending substantially parallel to a top surface/face of the knob.

Some vehicles (e.g., those with active front steer) have a power steering assist system configuration that allows a steering wheel to be partially decoupled from movement of the steered wheels of such a vehicle. Accordingly, the steering wheel can be rotated independent of the manner in which the power steering assist system of the vehicle controls the steered wheels (e.g., as commanded by vehicle steering information provided by a power steering assist system control module from a trailer backup assist system control module configured in accordance with one embodiment). As such, in these types of vehicles where the steering wheel can be selectively decoupled from the steered wheels to allow independent operation thereof, trailer steering information of a trailer backup assist system configured in accordance with the disclosed subject matter can be provided through rotation of the steering wheel. Accordingly, it is disclosed herein that in certain embodiments, the steering wheel is an embodiment of a rotational control input device in the context of the disclosed subject matter. In such embodiments, the steering wheel would be biased (e.g., by an apparatus that is selectively engageable/activatable) to an at-rest position between opposing rotational ranges of motion.

The hitch angle detection apparatus **130**, which operates in conjunction with a hitch angle detection component **155** of the trailer **110**, provides the trailer backup assist control module **120** with information relating to an angle between the vehicle **100** and the trailer **110** (i.e., hitch angle information). In a preferred embodiment, the hitch angle detection apparatus **130** is a camera-based apparatus such as, for example, an existing rear view camera of the vehicle **100** that images (i.e., visually monitors) a target (i.e., the hitch angle detection component **155**) attached to the trailer **110** as the trailer **110** is being backed by the vehicle **100**. Preferably, but not necessarily, the hitch angle detection component **155** is a dedicated component (e.g., an item attached to/integral with a surface of the trailer **110** for the express purpose of being recognized by the hitch angle detection apparatus **130**). Alternatively, the

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hitch angle detection apparatus **130** can be a device that is physically mounted on a hitch component of the vehicle **100** and/or a mating hitch component of the trailer **110** for determining an angle between centerline longitudinal axes of the vehicle **100** and the trailer **110**. The hitch angle detection apparatus **130** can be configured for detecting a jackknife enabling condition and/or related information (e.g., when a hitch angle threshold has been met).

The power steering assist control module **135** provides the trailer backup assist control module **120** with information relating to a rotational position (e.g., angle) of the steering wheel angle and/or a rotational position (e.g., turning angle(s)) of steered wheels of the vehicle **100**. In certain embodiments, the trailer backup assist control module **120** can be an integrated component of the power steering assist system **115**. For example, the power steering assist control module **135** can include a trailer backup assist algorithm for generating vehicle steering information as a function of all or a portion of information received from the trailer backup steering input apparatus **125**, the hitch angle detection apparatus **130**, the power steering assist control module **135**, the brake system control module **145**, and the powertrain control module **150**.

The brake system control module **145** provides the trailer backup assist control module **120** with information relating to vehicle speed. Such vehicle speed information can be determined from individual wheel speeds as monitored by the brake system control module **145** or may be provided by an engine control module with signal plausibility. Vehicle speed may also be determined from an engine control module. In some instances, individual wheel speeds can also be used to determine a vehicle yaw rate and such yaw rate can be provided to the trailer backup assist control module **120** for use in determining the vehicle steering information. In certain embodiments, the trailer backup assist control module **120** can provide vehicle braking information to the brake system control module **145** for allowing the trailer backup assist control module **120** to control braking of the vehicle **100** during backing of the trailer **110**. For example, using the trailer backup assist control module **120** to regulate speed of the vehicle **100** during backing of the trailer **110** can reduce the potential for unacceptable trailer backup conditions. Examples of unacceptable trailer backup conditions include, but are not limited to, a vehicle over speed condition, a high hitch angle rate, trailer angle dynamic instability, a calculated theoretical trailer jackknife condition (defined by a maximum vehicle steering angle, drawbar length, tow vehicle wheelbase and an effective trailer length), or physical contact jackknife limitation (defined by an angular displacement limit relative to the vehicle **100** and the trailer **110**), and the like. It is disclosed herein that the backup assist control module **120** can issue a signal corresponding to a notification (e.g., a warning) of an actual, impending, and/or anticipated unacceptable trailer backup condition.

The powertrain control module **150** interacts with the trailer backup assist control module **120** for regulating speed and acceleration of the vehicle **100** during backing of the trailer **110**. As mentioned above, regulation of the speed of the vehicle **100** is necessary to limit the potential for unacceptable trailer backup conditions such as, for example, jackknifing and trailer angle dynamic instability. Similar to high-speed considerations as they relate to unacceptable trailer backup conditions, high acceleration and high dynamic driver curvature requests can also lead to such unacceptable trailer backup conditions.

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#### Steering Input Apparatus

Referring now to FIG. 2, an embodiment of the trailer backup steering input apparatus **125** discussed in reference to FIG. 1 is shown. A rotatable control element in the form of a knob **170** is coupled to a movement sensing device **175**. The knob **170** is biased (e.g., by a spring return) to an at-rest position P(AR) between opposing rotational ranges of motion R(R), R(L). A first one of the opposing rotational ranges of motion R(R) is substantially equal to a second one of the opposing rotational ranges of motion R(L), R(R). To provide a tactile indication of an amount of rotation of the knob **170**, a force that biases the knob **170** toward the at-rest position P(AR) can increase (e.g., non-linearly) as a function of the amount of rotation of the knob **170** with respect to the at-rest position P(AR). Additionally, the knob **170** can be configured with position indicating detents such that the driver can positively feel the at-rest position P(AR) and feel the ends of the opposing rotational ranges of motion R(L), R(R) approaching (e.g., soft end stops).

The movement sensing device **175** is configured for sensing movement of the knob **170** and outputting a corresponding signal (i.e., movement sensing device signal) to the trailer assist backup input apparatus **125** shown in FIG. 1. The movement sensing device signal is generated as a function of an amount of rotation of the knob **170** with respect to the at-rest position P(AR), a rate movement of the knob **170**, and/or a direction of movement of the knob **170** with respect to the at-rest position P(AR). As will be discussed below in greater detail, the at-rest position P(AR) of the knob **170** corresponds to a movement sensing device signal indicating that the vehicle **100** should be steered such that the trailer **110** is backed along a substantially straight path (zero trailer curvature request from the driver) as defined by a centerline longitudinal axis of the trailer **110** when the knob **170** was returned to the at-rest position P(AR) and a maximum clockwise and anti-clockwise position of the knob **170** (i.e., limits of the opposing rotational ranges of motion R(R), R(L)) each correspond to a respective movement sensing device signal indicating a tightest radius of curvature (i.e., most acute trajectory) of a path of travel of the trailer **110** that is possible without the corresponding vehicle steering information causing a jackknife condition. In this regard, the at-rest position P(AR) is a zero curvature commanding position with respect to the opposing rotational ranges of motion R(R), R(L). It is disclosed herein that a ratio of a commanded curvature of a path of a trailer (e.g., radius of a trailer trajectory) and a corresponding amount of rotation of the knob can vary (e.g., non-linearly) over each one of the opposing rotational ranges of motion P(L), P(R) of the knob **170**. It is also disclosed therein that the ratio can be a function of vehicle speed, trailer geometry, vehicle geometry, hitch geometry and/or trailer load.

Use of the knob **170** decouples trailer steering inputs from being made at a steering wheel of the vehicle **100**. In use, as a driver of the vehicle **100** backs the trailer **110**, the driver can turn the knob **170** to indicate a desired curvature of a path of the trailer **110** to follow and returns the knob **170** to the at-rest position P(AR) for causing the trailer **110** to be backed along a straight line. Accordingly, in embodiments of trailer backup assist systems where the steering wheel remains physically coupled to the steerable wheels of a vehicle during backup of an attached trailer, a rotatable control element configured in accordance with the disclosed subject matter (e.g., the knob **170**) provides a simple and user-friendly means of allowing a driver of a vehicle to input trailer steering commands.

It is disclosed herein that a rotational control input device configured in accordance with embodiments of the disclosed

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subject matter (e.g., the knob **170** and associated movement sensing device) can omit a means for being biased to an at-rest position between opposing rotational ranges of motion. Lack of such biasing allows a current rotational position of the rotational control input device to be maintained until the rotational control input device is manually moved to a different position. Preferably, but not necessarily, when such biasing is omitted, a means is provided for indicating that the rotational control input device is positioned in a zero curvature commanding position (e.g., at the same position as the at-rest position in embodiments where the rotational control input device is biased). Examples of means for indicating that the rotational control input device is positioned in the zero curvature commanding position include, but are not limited to, a detent that the rotational control input device engages when in the zero curvature commanding position, a visual marking indicating that the rotational control input device is in the zero curvature commanding position, an active vibratory signal indicating that the rotational control input device is in or approaching the zero curvature commanding position, an audible message indicating that the rotational control input device is in or approaching the zero curvature commanding position, and the like.

It is also disclosed herein that embodiments of the disclosed subject matter can be configured with a control input device that is not rotational (i.e., a non-rotational control input device). Similar to a rotational control input device configured in accordance with embodiments of the disclosed subject matter (e.g., the knob **170** and associated movement sensing device), such a non-rotational control input device is configured to selectively provide a signal causing a trailer to follow a path of travel segment that is substantially straight and to selectively provide a signal causing the trailer to follow a path of travel segment that is substantially curved. Examples of such a non-rotational control input device include, but are not limited to, a plurality of depressible buttons (e.g., curve left, curve right, and travel straight), a touch screen on which a driver traces or otherwise inputs a curvature for path of travel commands, a button that is translatable along an axis for allowing a driver to input path of travel commands, or joystick type input and the like.

The trailer backup steering input apparatus **125** can be configured to provide various feedback information to a driver of the vehicle **100**. Examples of situation that such feedback information can include, but are not limited to, a status of the trailer backup assist system **105** (e.g., active, in standby (e.g., when driving forward to reduce the hitch angle and zero hitch angle to remove bias), faulted, inactive, etc.), that a curvature limit has been reached (i.e., maximum commanded curvature of a path of travel of the trailer **110**), and/or a graphical representation of the vehicle and trailer orientation state. To this end, the trailer backup steering input apparatus **125** can be configured to provide a tactile feedback signal (e.g., a vibration through the knob **170**) as a warning if any one of a variety of conditions occur. Examples of such conditions include, but are not limited to, the trailer **110** approaching jackknife, the trailer backup assist system **105** has had a failure, the trailer backup assist system **105** has detected a fault, the trailer backup assist system **105** or other system of the vehicle **100** has predicted a collision on the present path of travel of the trailer **110**, the trailer backup system **105** has restricted a commanded curvature of a trailer's path of travel (e.g., due to excessive speed or acceleration of the vehicle **100**), and the like. Still further, it is disclosed that the trailer backup steering input apparatus **125** can use illumination (e.g., an LED **180**) and/or an audible signal output (e.g., an audible output device **185** or through attached

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vehicle audio speakers) to provide certain feedback information (e.g., notification/warning of an unacceptable trailer backup condition).

Referring now to FIGS. **2** and **3**, an example of using the trailer backup steering input apparatus **125** for dictating a curvature of a path of travel (POT) of a trailer (i.e., the trailer **110** shown in FIG. **1**) while backing up the trailer with a vehicle (i.e., the vehicle **100** in FIGS. **1** and **2**) is shown. In preparation of backing the trailer **110**, the driver of the vehicle **100** drives the vehicle **100** forward along a pull-thru path (PTP) to position the vehicle **100** and trailer **110** at a first backup position B1. In the first backup position B1, the vehicle **100** and trailer **110** are longitudinally aligned with each other such that a longitudinal centerline axis L1 of the vehicle **100** is aligned with (e.g., parallel with or coincidental with) a longitudinal centerline axis L2 of the trailer **110**. It is disclosed herein that such alignment of the longitudinal axes L1, L2 at the onset of an instance of trailer backup functionality is not a requirement for operability of a trailer backup assist system configured in accordance with the disclosed subject matter.

After activating the trailer backup assist system **105** (e.g., before, after, or during the pull-thru sequence), the driver begins to back the trailer **110** by reversing the vehicle **100** from the first backup position B1. So long as the knob **170** of the trailer backup steering input apparatus **125** remains in the at-rest position P(AR), the trailer backup assist system **105** will steer the vehicle **100** as necessary for causing the trailer **110** to be backed along a substantially straight path of travel as defined by the longitudinal centerline axis L2 of the trailer **110** at the time when backing of the trailer **110** began. When the trailer reaches the second backup position B2, the driver rotates the knob **170** to command the trailer **110** to be steered to the right (i.e., a knob position R(R) clockwise rotation). Accordingly, the trailer backup assist system **105** will steer the vehicle **100** for causing the trailer **110** to be steered to the right as a function of an amount of rotation of the knob **170** with respect to the at-rest position P(AR), a rate movement of the knob **170**, and/or a direction of movement of the knob **170** with respect to the at-rest position P(AR). Similarly, the trailer **110** can be commanded to steer to the left by rotating the knob **170** to the left. When the trailer reaches backup position B3, the driver allows the knob **170** to return to the at-rest position P(AR) thereby causing the trailer backup assist system **105** to steer the vehicle **100** as necessary for causing the trailer **110** to be backed along a substantially straight path of travel as defined by the longitudinal centerline axis L2 of the trailer **110** at the time when the knob **170** was returned to the at-rest position P(AR). Thereafter, the trailer backup assist system **105** steers the vehicle **100** as necessary for causing the trailer **110** to be backed along this substantially straight path to the fourth backup position B4. In this regard, arcuate portions of a path of travel POT of the trailer **110** are dictated by rotation of the knob **170** and straight portions of the path of travel POT are dictated by an orientation of the centerline longitudinal axis L2 of the trailer when the knob **170** is in/returned to the at-rest position P(AR).

In order to activate the trailer backup assist system described above in FIGS. **1-3**, the driver interacts with the trailer backup assist system and the trailer backup assist system interacts with the vehicle environment. The trailer backup assist system automatically steers as the driver reverses the vehicle. As discussed above, the driver controls the trailer trajectory by using a steering knob to input desired trailer curvature. The trailer backup assist algorithm determines the vehicle steering angle to achieve the desired trailer

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curvature, and the driver controls the throttle and brake while the trailer backup assist system controls the steering.

FIG. 4 shows a method **200** for implementing trailer backup assist functionality in accordance with one embodiment. In a preferred embodiment, the method **200** for implementing trailer backup assist functionality can be carried out using the trailer backup assist architecture discussed above in reference to the vehicle **100** and trailer **110** of FIG. 1. Accordingly, trailer steering information is provided through use of a rotational control input device (e.g., the knob **170** discussed in reference to FIG. 2).

An operation **202** is performed for receiving a trailer backup assist request. Examples of receiving the trailer backup assist request include activating the trailer backup assist system and providing confirmation that the vehicle and trailer are ready to be backed. After receiving a trailer backup assist request (i.e., while the vehicle is being reversed), an operation **204** is performed for receiving a trailer backup information signal. Examples of information carried by the trailer backup information signal include, but are not limited to, information from the trailer backup steering input apparatus **125**, information from the hitch angle detection apparatus **130**, information from the power steering assist control module **135**, information from the brake system control module **145**, and information from the powertrain control module **150**. It is disclosed herein that information from the trailer backup steering input apparatus **125** preferably includes trailer path curvature information characterizing a desired curvature for the path of travel of the trailer, such as provided by the trailer backup steering input apparatus **125** discussed above in reference to FIGS. 1 and 2. In this manner, the operation **204** for receiving the trailer backup information signal can include receiving trailer path curvature information characterizing the desired curvature for the path of travel of the trailer.

If the trailer backup information signal indicates that a change in curvature of the trailer's path of travel is requested (i.e., commanded via the knob **170**), an operation **206** is performed for determining vehicle steering information for providing the requested change in curvature of the trailer's path of travel. Otherwise, an operation **208** is performed for determining vehicle steering information for maintaining a current straight-line heading of the trailer (i.e., as defined by the longitudinal centerline axis of the trailer). Thereafter, an operation **210** is performed for providing the vehicle steering information to a power steering assist system of the vehicle, followed by an operation **212** being performed for determining the trailer backup assist status. If it is determined that trailer backup is complete, an operation **214** is performed for ending the current trailer backup assist instance. Otherwise the method **200** returns to the operation **204** for receiving trailer backup information. Preferably, the operation for receiving the trailer backup information signal, determining the vehicle steering information, providing the vehicle steering information, and determining the trailer backup assist status are performed in a monitoring fashion (e.g., at a high rate of speed of a digital data processing device). Accordingly, unless it is determined that reversing of the vehicle for backing the trailer is completed (e.g., due to the vehicle having been successfully backed to a desired location during a trailer backup assist instance, the vehicle having to be pulled forward to begin another trailer backup assist instance, etc.), the method **200** will continually be performing the operations for receiving the trailer backup information signal, determining the vehicle steering information, providing the vehicle steering information, and determining the trailer backup assist status.

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It is disclosed herein that the operation **206** for determining vehicle steering information for providing the requested change in curvature of the trailer's path of travel preferably includes determining vehicle steering information as a function of trailer path curvature information contained within the trailer backup information signal. As will be discussed below in greater detail, determining vehicle steering information can be accomplished through a low order kinematic model defined by the vehicle and the trailer. Through such a model, a relationship between the trailer path curvature and commanded steering angles of steered wheels of the vehicle can be generated for determining steering angle changes of the steered wheels for achieving a specified trailer path curvature. In this manner, the operation **206** for determining vehicle steering information can be configured for generating information necessary for providing trailer path curvature control in accordance with the disclosed subject matter.

In some embodiments of the disclosed subject matter, the operation **210** for providing the vehicle steering information to the power steering assist system of the vehicle causes the steering system to generate a corresponding steering command as a function of the vehicle steering information. The steering command is interpretable by the steering system and is configured for causing the steering system to move steered wheels of the steering system for achieving a steered angle as specified by the vehicle steering information. Alternatively, the steering command can be generated by a controller, module or computer external to the steering system (e.g., a trailer backup assist control module) and be provided to the steering system.

In parallel with performing the operations for receiving the trailer backup information signal, determining the vehicle steering information, providing the vehicle steering information, and determining the trailer backup assist status, the method **200** performs an operation **216** for monitoring the trailer backup information for determining if an unacceptable trailer backup condition exists. Examples of such monitoring include, but are not limited to assessing a hitch angle to determine if a hitch angle threshold is exceeded, assessing a backup speed to determine if a backup speed threshold is exceeded, assessing vehicle steering angle to determine if a vehicle steering angle threshold is exceeded, assessing other operating parameters (e.g., vehicle longitudinal acceleration, throttle pedal demand rate and hitch angle rate) for determining if a respective threshold value is exceeded, and the like. Backup speed can be determined from wheel speed information obtained from one or more wheel speed sensors of the vehicle. If it is determined that an unacceptable trailer backup condition exists, an operation **218** is performed for causing the current path of travel of the trailer to be inhibited (e.g., stopping motion of the vehicle), followed by the operation **214** being performed for ending the current trailer backup assist instance. It is disclosed herein that prior to and/or in conjunction with causing the current trailer path to be inhibited, one or more actions (e.g., operations) can be implemented for providing the driver with feedback (e.g., a warning) that such an unacceptable hitch angle condition is impending or approaching. In one example, if such feedback results in the unacceptable hitch angle condition being remedied prior to achieving a critical condition, the method can continue with providing trailer backup assist functionality in accordance with operations **204-212**. Otherwise, the method can proceed to operation **214** for ending the current trailer backup assist instance. In conjunction with performing the operation **214** for ending the current trailer backup assist instance, an operation can be performed for controlling movement of the vehicle to correct or limit a jackknife con-

dition (e.g., steering the vehicle, decelerating the vehicle, limiting magnitude and/or rate of driver requested trailer curvature input, limiting magnitude and/or rate of the steering command, and/or the like to preclude the hitch angle from being exceeded).

#### Curvature Control Algorithm

Turning now to a discussion of a kinematic model used to calculate a relationship between a curvature of a path of travel of a trailer and the steering angle of a vehicle towing the trailer, a low order kinematic model can be desirable for a trailer backup assist system configured in accordance with some embodiments. To achieve such a low order kinematic model, certain assumptions are made with regard to parameters associated with the vehicle/trailer system. Examples of such assumptions include, but are not limited to, the trailer being backed by the vehicle at a relatively low speed, wheels of the vehicle and the trailer having negligible (e.g., no) slip, tires of the vehicle having negligible (e.g., no) lateral compliance, tires of the vehicle and the trailer having negligible (e.g., no) deformation, actuator dynamics of the vehicle being negligible, the vehicle and the trailer exhibiting negligible (e.g., no) roll or pitch motions.

As shown in FIG. 5, for a system defined by a vehicle 302 and a trailer 304, the kinematic model 300 is based on various parameters associated with the vehicle 302 and the trailer 304. These kinematic model parameters include:

δ: steering angle at steered front wheels 306 of the vehicle 302;

α: yaw angle of the vehicle 302;

β: yaw angle of the trailer 304;

γ: hitch angle (γ=β-α);

W: wheel base of the vehicle 302;

L: length between hitch point 308 and rear axle 310 of the vehicle 302;

D: length between hitch point 308 and axle length 312 of the trailer 304 (axle length 312 may be an effective, or equivalent, axle length for a trailer having a multiple axle configuration; and

r<sub>2</sub>: curvature radius for the trailer 304.

The kinematic model 300 of FIG. 5 reveals a relationship between trailer path radius of curvature r<sub>2</sub> at the midpoint 314 of an axle 312 of the trailer 304, steering angle δ of the steered wheels 306 of the vehicle 302, and the hitch angle γ. As shown in the equation below, this relationship can be expressed to provide the trailer path curvature κ<sub>2</sub> such that, if γ is given, the trailer path curvature κ<sub>2</sub> can be controlled based on regulating the steering angle δ (where β̇ is trailer yaw rate and η̇ is trailer velocity).

$$\kappa_2 = \frac{1}{r_2} = \frac{\dot{\beta}}{\dot{\eta}} = \frac{\left(W + \frac{KV^2}{g}\right) \sin \gamma + L \cos \gamma \tan \delta}{D \left( \left(W + \frac{KV^2}{g}\right) \cos \gamma - L \sin \gamma \tan \delta \right)}$$

Or, this relationship can be expressed to provide the steering angle δ as a function of trailer path curvature κ<sub>2</sub> and hitch angle γ.

$$\delta = \tan^{-1} \left( \frac{\left(W + \frac{KV^2}{g}\right) [\kappa_2 D \cos \gamma - \sin \gamma]}{D \kappa_2 \sin \gamma + L \cos \gamma} \right) = F(\gamma, \kappa_2, K)$$

Accordingly, for a particular vehicle and trailer combination, certain kinematic model parameters (e.g., D, W and L) are constant and assumed known. V is the vehicle longitudinal speed and g is the acceleration due to gravity. K is a speed dependent parameter which when set to zero makes the calculation of steering angle independent of vehicle speed. For example, vehicle-specific kinematic model parameters can be predefined in an electronic control system of a vehicle and trailer-specific kinematic model parameters can be inputted by a driver of the vehicle. Trailer path curvature κ<sub>2</sub> is determined from the driver input via a trailer backup steering input apparatus. Through the use of the equation for providing steering angle, a corresponding steering command can be generated for controlling a steering system (e.g., an actuator thereof) of the vehicle.

FIG. 6 shown an example of a trailer path curvature function plot 400 for a rotary-type trailer backup steering input apparatus (e.g., the trailer backup steering input apparatus 125 discussed above in reference to FIGS. 1 and 2). A value representing trailer path curvature (e.g., trailer path curvature κ<sub>2</sub>) is provided as an output signal from the rotary-type trailer backup steering input apparatus as a function of user input movement. In this example, a curve 402 specifying trailer path curvature relative to user input (e.g., amount of rotation) at a rotary input device (e.g., a knob) is defined by a cubic function. However, a skilled person will appreciate that embodiments of the disclosed subject matter are not limited to any particular function between a magnitude and/or rate of input at a trailer backup steering input apparatus (e.g., knob rotation) and a resulting trailer path curvature value.

#### Jackknife Detection

Referring to FIG. 5, in preferred embodiments of the disclosed subject matter, it is desirable to limit the potential for the vehicle 302 and the trailer 304 to attain a jackknife angle (i.e., the vehicle/trailer system achieving a jackknife condition). A jackknife angle γ(j) refers to a hitch angle γ that while backing cannot be overcome by the maximum steering input for a vehicle such as, for example, the steered front wheels 306 of the vehicle 302 being moved to a maximum steered angle δ at a maximum rate of steering angle change. The jackknife angle γ(j) is a function of a maximum wheel angle for the steered wheel 306 of the vehicle 302, the wheel base W of the vehicle 302, the distance L between hitch point 308 and the rear axle 310 of the vehicle 302, and the length D between the hitch point 308 and the effective axle 312 of the trailer 304 when the trailer has multiple axles. The effective axle 312 may be the actual axle for a single axle trailer or an effective axle location for a trailer with multiple axles. When the hitch angle γ for the vehicle 302 and the trailer 304 achieves or exceeds the jackknife angle γ(j), the vehicle 302 must be pulled forward to reduce the hitch angle γ. Thus, for limiting the potential for a vehicle/trailer system attaining a jackknife angle, it is preferable to control the yaw angle of the trailer while keeping the hitch angle of the vehicle/trailer system relatively small.

Referring to FIGS. 5 and 7, a steering angle limit for the steered front wheels 306 requires that the hitch angle γ cannot exceed the jackknife angle γ(j), which is also referred to as a critical hitch angle. Thus, under the limitation that the hitch angle γ cannot exceed the jackknife angle γ(j), the jackknife angle γ(j) is the hitch angle γ that maintains a circular motion for the vehicle/trailer system when the steered wheels 306 are at a maximum steering angle δ(max). The steering angle for circular motion with hitch angle is defined by the following equation.

$$\tan \delta_{\max} = \frac{w \sin \gamma_{\max}}{D + L \cos \gamma_{\max}}$$

Solving the above equation for hitch angle allows jackknife angle  $\gamma(j)$  to be determined. This solution, which is shown in the following equation, can be used in implementing trailer backup assist functionality in accordance with the disclosed subject matter for monitoring hitch angle in relation to jackknife angle.

$$\cos \gamma = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

where,

$$a = L^2 \tan^2 \delta(\max) + W^2;$$

$$b = 2LD \tan^2 \delta(\max); \text{ and}$$

$$c = D^2 \tan^2 \delta(\max) - W^2.$$

In certain instances of backing a trailer, a jackknife enabling condition can arise based on current operating parameters of a vehicle in combination with a corresponding hitch angle. This condition can be indicated when one or more specified vehicle operating thresholds are met while a particular hitch angle is present. For example, although the particular hitch angle is not currently at the jackknife angle for the vehicle and attached trailer, certain vehicle operating parameters can lead to a rapid (e.g., uncontrolled) transition of the hitch angle to the jackknife angle for a current commanded trailer path curvature and/or can reduce an ability to steer the trailer away from the jackknife angle. One reason for a jackknife enabling condition is that trailer curvature control mechanisms (e.g., those in accordance with the disclosed subject matter) generally calculate steering commands at an instantaneous point in time during backing of a trailer. However, these calculations will typically not account for lag in the steering control system of the vehicle (e.g., lag in a steering EPAS controller). Another reason for the jackknife enabling condition is that trailer curvature control mechanisms generally exhibit reduced steering sensitivity and/or effectiveness when the vehicle is at relatively high speeds and/or when undergoing relatively high acceleration.

#### Jackknife Countermeasures

FIG. 8 shows a method 500 for implementing jackknife countermeasures functionality in accordance with an embodiment of the disclosed subject matter for a vehicle and attached trailer. Trailer backup assist functionality in accordance with the disclosed subject matter can include jackknife countermeasures functionality. Alternatively, jackknife countermeasures functionality in accordance with one embodiment can be implemented separately from other aspects of trailer backup assist functionality.

The method 500 begins when operation 502 is performed for receiving jackknife determining information characterizing a jackknife enabling condition of the vehicle-trailer combination at a particular point in time (e.g., at the point in time when the jackknife determining information was sampled). Examples of the jackknife determining information includes, but are not limited to, information characterizing a hitch angle, information characterizing a vehicle accelerator pedal transient state, information characterizing a speed of the vehicle, information characterizing longitudinal acceleration of the vehicle, information characterizing a brake torque

being applied by a brake system of the vehicle, information characterizing a powertrain torque being applied to driven wheels of the vehicle, and information characterizing the magnitude and rate of driver requested trailer curvature. The operation 502 for receiving jackknife determining information can be the first operation in a sampling process where jackknife determining information is sampled upon initiation of an instance of implementing jackknife countermeasures functionality. In this regard, jackknife determining information would be continually monitored such as, for example, by an electronic control unit (ECU) that carries out trailer backup assist (TBA) functionality. As discussed above in reference to FIG. 5, a kinematic model representation of the vehicle and the trailer can be used to determine a jackknife angle for the vehicle-trailer combination. However, the disclosed subject matter is not unnecessarily limited to any specific approach for determining the jackknife angle.

After receiving the jackknife determining information, an operation 504 is performed for assessing the jackknife determining information for determining if the vehicle-trailer combination attained the jackknife enabling condition at the particular point in time. The objective of the operation 504 for assessing the jackknife determining information is determining if a jackknife enabling condition has been attained at the point in time defined by the jackknife determining information. If it is determined that a jackknife enabling condition is not present at the particular point in time, the method 500 returns to the operation 502 for receiving another instance of the jackknife determining information. If it is determined that a jackknife enabling condition is present at the particular point in time, an operation 506 is performed for determining an applicable countermeasure or countermeasures to implement. Accordingly, in some embodiments, an applicable countermeasure will be selected dependent upon a parameter identified as being a key influencer of the jackknife enabling condition. However, in other embodiments, an applicable countermeasure will be selected as being most able to readily alleviate the jackknife enabling condition. In still other embodiment, a predefined countermeasure or predefined set of countermeasures may be the applicable countermeasure(s).

The objective of a countermeasure in the context of the disclosed subject matter (i.e., a jackknife reduction countermeasure) is to alleviate a jackknife enabling condition. To this end, such a countermeasure can be configured to alleviate the jackknife enabling condition using a variety of different strategies. In a vehicle speed sensitive countermeasure strategy, actions taken for alleviating the jackknife enabling condition can include overriding and/or limiting driver requested trailer radius of curvature (e.g., being requested via a trailer backup steering input apparatus configured in accordance with the disclosed subject matter) as a function of vehicle speed (e.g., via a lookup table correlating radius of curvature limits to vehicle speed as shown in FIG. 6). In a countermeasure strategy where trailer curvature requests are limited as a function of speed and driver curvature command transient rates, actions taken for alleviating the jackknife enabling condition can include rate limiting trailer curvature command transients as requested by a driver above a predefined vehicle speed whereas, under the predefined vehicle speed, the as-requested trailer curvature are not rate limited. In a torque limiting countermeasure strategy, actions taken for alleviating the jackknife enabling condition can include application of full available powertrain torque being inhibited when the jackknife enabling condition is present while the vehicle is above a predefined speed and application of full available powertrain torque being allowed when the vehicle speed is reduced

below the predefined speed while in the torque inhibiting mode. As opposed to a fixed predefined speed, the torque limiting countermeasure strategy can utilize a speed threshold that is a function of hitch angle (i.e., speed threshold inversely proportional to hitch angle acuteness). In a driver accelerator pedal transient detection countermeasure strategy, actions taken for alleviating the jackknife enabling condition can include overriding and/or limiting driver requested trailer radius of curvature as a function of transient accelerator pedal requests (e.g., requested trailer radius of curvature limited when a large accelerator pedal transient is detected). In a hitch angle rate sensitive countermeasure strategy, actions taken for alleviating the jackknife enabling condition can include using hitch angle rate in a predefined or calculated mapping with current hitch angle position to limit driver requested trailer radius of curvature. Accordingly, in view of the disclosures made herein, a skilled person will appreciate that embodiments of the disclosed subject matter are not unnecessarily limited to a countermeasure strategy of any particular configuration.

As disclosed above, implementation of trailer backup assist functionality in accordance with the disclosed subject matter can utilize a kinematic model for determining steering control information, jackknife enabling conditions, and jackknife angle. Such a kinematic model has many parameters than can influence trailer curvature control effectiveness. Examples of these parameters include, but are not limited to, the vehicle wheelbase, understeer gradient gain, vehicle track width, maximum steer angle at the vehicle front wheels, minimum turning radius of vehicle, maximum steering rate able to be commanded by the steering system, hitch ball to trailer axle length, and vehicle rear axle to hitch ball length. Sensitivity analysis for a given kinematic model can be used to provide an understanding (e.g., sensitivity) of the relationships between such parameters, thereby providing information necessary for improving curvature control performance and for reducing the potential for jackknife enabling conditions. For example, through an understanding of the sensitivity of the parameters of a kinematic model, scaling factors can be used with speed dependent jackknife countermeasures to reduce jackknife potential (e.g., for special applications such as short wheelbase conditions).

Still referring to FIG. 8, after determining the applicable countermeasure(s), an operation **508** is performed for implementing the chosen jackknife countermeasure(s) and an operation **510** is performed for initiating a jackknife warning. As discussed above in regard to countermeasure strategies, implementing the jackknife countermeasure(s) can include commanding a speed controlling system of the vehicle to transition to an altered state of operation in which a speed of the vehicle is reduced, commanding the steering control system of the vehicle to transition to an altered state of operation in which a radius of curvature of a path of the trailer is increased, command the steering control system of the vehicle to transition to an altered state of operation in which a decrease in the radius of the curvature of the path of the trailer is inhibited, commanding a brake control system of the vehicle to apply brake torque to reduce vehicle speed/inhibit vehicle acceleration, and/or commanding a powertrain control system of the vehicle to inhibit full available powertrain torque from being delivered to driven wheels of the vehicle until another jackknife enabling parameter (e.g., vehicle speed) is below a defined threshold. In certain embodiments of the disclosed subject matter, the jackknife warning is provided to the driver using at least one vehicle control system through which the jackknife countermeasure is implemented. Speed reduction, in addition to applying the brakes, can be

accomplished by any number of means such as, for example, limiting throttle inputs (e.g., via a terrain management feature) and/or transitioning a transmission to a reverse low gear if the vehicle is equipped with a multi-range reverse gear transmission. Examples of such system-specific warning approach include, but are not limited to, providing a warning through an accelerator pedal of the vehicle (e.g., via haptic feedback) if the countermeasure includes limiting speed of the vehicle and/or providing a warning through an input element (e.g., knob) of a trailer backup steering input apparatus of the vehicle (e.g., via haptic feedback if the countermeasure includes limiting driver requested trailer radius of curvature), through haptic seat vibration warning, through a visual warning (e.g., through a visual display apparatus of the towing vehicle) and/or through audible warnings (e.g., through an audio output apparatus of the towing vehicle), or the like. One embodiment of utilizing warnings relating to vehicle speed as it relates to onset or presence of a jackknife enabling condition includes implementation of a dual stage warning. For example, when a backing speed of the vehicle increases sufficiently for causing a speed of the vehicle to reach a lower (i.e., first) speed threshold during backing of the trailer, a driver of the vehicle would be provided with a first warning indication (e.g., via haptic, audible, and/or visual means as implemented by the trailer backup assist system) for informing the driver that there is the need to reduce the speed of the vehicle to alleviate or preclude the jackknife enabling condition. If the driver does not correspondingly respond by causing a speed of the vehicle to be reduced (or not to further increase) and the vehicle continues to gain speed such that it passes a higher (i.e., a second) speed threshold, the driver of the vehicle would be provided with a second warning indication (e.g., a more severe haptic, audible, and/or visual means as implemented by the trailer backup assist system) for informing the driver that there is an immediate need to reduce the speed of the vehicle to alleviate or preclude the jackknife enabling condition. The first and/or the second speed indication warnings can be implemented in conjunction with a respective speed limiting countermeasure measures (e.g., the trailer backup assist system causing activation of a brake system of the vehicle and/or reducing a throttle position of the vehicle).

#### Human Machine Interface

In order to implement the control features discussed above with respect to methods described in FIG. 5 and FIG. 8, a driver must interact with the trailer backup assist system **105** to configure the system **105**. The vehicle **100** is also equipped, as shown in FIG. 9, with a human machine interface (HMI) device **102** to implement trailer backup assist functionality through driver interaction with the HMI device **102**.

FIG. 9 shows an example of an HMI device **102** in the vehicle that a driver uses to interact with the trailer backup assist system **105**. The driver is presented with multiple menus **104** (only one example menu is shown in FIG. 9) displayed by way of the HMI **102**. The HMI menus **104** assist the driver through modules (shown in FIGS. 10 and 11) that setup **600**, calibrate **700**, and activate **800** the trailer backup assist system **105** so that control methods **200**, **500** may be implemented to assist the driver with the backup of the trailer shown generally as a flow diagram in FIGS. 10 and 11, and to be discussed in greater detail later herein. Each module is directed to particular elements, or features, which are used to configure the trailer backup assist system to accurately implement control methods **200**, **500**. While each module is described with reference to particular features of the disclosed subject matter, it should be noted that each module is not necessarily limited to the particular features described in

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the examples herein. It is possible to rearrange the modules or to replace elements or features of a module without departing from the scope of the disclosed subject matter.

The trailer backup assist system **105** will guide a driver through the steps necessary to connect a trailer and attach a target. The driver may activate the setup by way of the backup steering input apparatus **125**, for example by turning or pushing the rotary knob, or may merely making a selection for the trailer backup assist system from a menu on the HMI device **102**. Referring to FIG. **10**, a driver initiates the trailer backup assist system through the trailer backup assist steering input apparatus. In the case of a rotary knob, the driver presses or rotates the knob to initiate the trailer backup assist system. The system will guide the driver through the steps of connecting **580** a compatible trailer **110**. A compatible trailer is one that pivots at a single point relative to the vehicle and behind the rear axle of the vehicle.

Once the system is selected by either the trailer backup steering input apparatus **125** or the HMI device **102**, the system will guide the driver to prepare the vehicle and vehicle trailer combination as necessary. The vehicle **100** should be turned “on” and the vehicle **100** should be in “park” **590**. In the event the vehicle **100** is on but is traveling at a speed that is greater than a predetermined limit, for example five miles per hour, the trailer backup assist system **105** will become inactive and inaccessible to the driver. The trailer backup assist system **105** setup module **600** will not begin or will be exited **585**. If the type of trailer **110** selected by the driver is a trailer **110** that is not compatible with the trailer backup assist system **105**, the setup module **600** will be exited **585** or will not begin. In the event, the trailer **110** is compatible with the trailer backup assist system **105**, the setup module **600** verifies that the vehicle **100** gear shift mechanism is in “park.” Again, in the event the vehicle is not “on” and the gear shift mechanism is not on “park,” the setup module will not begin **585**.

Upon connection **580** of a compatible trailer **110**, the vehicle **100** being “on” **590** and the vehicle **100** being in “park” **590**, the HMI **102** will present a menu **104** that has a “Towing” mode option to be selected by the driver. The driver selects “Towing” mode and a menu **104** is presented that provides a “Trailer Options” selection. The driver then selects a “Trailer Options” mode from the “Towing” menu. The driver is prompted to either “add a trailer” or “select a trailer” from a menu **104** presented on the HMI device and the “Setup” module **600** has begun. For certain camera-based hitch angle detection systems, an operation **602** is performed wherein a warning menu may be presented to the driver, by way of the HMI, informing the driver that the trailer must be in a straight line, meaning there is no angle at the hitch between the vehicle and the trailer. The warning indicates that the driver may need to take corrective action, for example, pull the vehicle forward in order to align the trailer and the vehicle as required for the setup **600**. A generic or static graphic may be presented by way of the HMI **102** to assist the driver in visually recognizing the alignment between the trailer **110** and the vehicle **100** that is necessary in order to properly setup and calibrate the trailer backup assist system **105**. The driver applies any corrections **603** in that the driver makes any necessary adjustment he has been alerted to and indicates, by acknowledging that corrective actions have been applied **603** and that the trailer is in line with the vehicle. Other hitch angle detection systems may not need the driver to straighten the trailer during setup mode.

To aid the driver in the setup process, the reverse back lights, or any other supplemental lighting that may be available on the vehicle, are illuminated **604**. In the event the trailer

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is a new trailer, one that has not been attached to the vehicle before or has not been previously stored in the trailer backup assist system, the driver is presented **606** with an option to either name the trailer or select a previously stored trailer configuration. Naming the trailer **608** allows the trailer to be easily identified the next time it is attached to the vehicle so that the driver does not have to repeat the setup process. The driver either enters a unique name to identify the trailer that is to be stored in the trailer backup assist system or selects a previously stored trailer configuration associated with the attached trailer. The trailer backup assist system will not allow more than one trailer to have the same name. Therefore, if a driver attempts to name a trailer using a name that has already been applied to a previously stored trailer configuration, the HMI will display a message to the driver indicating so and requesting the driver enter a different name for the trailer configuration. In the case where a previously stored trailer configuration is available and selected **610** by the driver, certain steps in the setup process may be skipped.

The following discussion is directed to a first time trailer configuration for a camera-based hitch angle detection system. The driver is instructed **612** to place a hitch angle target on the trailer that is used for calibration purposes. A generic static image may be displayed on the HMI that provides direction to the driver as to placement of a target on the trailer that is used for hitch angle detection. The target placement is dependent upon the type of trailer being towed and therefore, options may be presented to the driver to aid the driver in selecting an appropriate trailer type. The static image may indicate areas that are acceptable for target placement as well as areas that are unacceptable for target placement. The static image indicating the appropriate areas for attaching the target may be an overlay of the rear view of the trailer hitch. Once the driver attaches the target to the trailer and indicates by way of the HMI that the target has been attached to the trailer the setup mode provides **614** visual feedback to the driver identifying that the target has been located, or acquired. The driver acknowledges **616**, by way of the HMI, that the target has been properly identified by the trailer backup assist system. Similarly, for a previously stored trailer configuration, the trailer will already have a target placed thereon. The trailer backup assist system will acquire the target and provide **614** visual feedback to the driver confirming acquisition of the target.

In the event the target is not acquired **614** after a predetermined amount of time lapses, the driver is notified **618** of the need to reposition the target and presented with possible corrective measures that may be taken. Possible corrective measures may be presented to the driver such as cleaning the camera lens, cleaning the target, replacing the target if it has been damaged or faded, pulling the vehicle-trailer combination forward to improve lighting conditions around the camera and/or target, and moving the target to an acceptable location. The driver applies the necessary corrections **603**. As mentioned above, some hitch angle detection systems may not require the driver to attach a target to the trailer during set up mode. The target and acquisition of the target are directed to camera-based hitch angle detection systems.

When the target is acquired **614** by the trailer backup assist system and the driver has acknowledged **616** the acquisition, the driver is then prompted through a series of menus to input **620** trailer measurement information that may be stored in the trailer backup assist system for a trailer configuration that is to be associated with the named trailer. The next time the same trailer is attached to the vehicle, its unique trailer configuration will already be stored and progress through the setup module will be faster or, in some cases, may be skipped



entirely. Generic static images may be displayed at the HMI screen in order to assist the driver with the measurement information. Visual examples, see FIG. 12, may be provided to aid the driver in identifying the location on the vehicle, the trailer or between the vehicle and trailer that the driver is being prompted to enter. In addition, numerical limits for the driver entered measurements are set within the trailer backup assist system and may be displayed to the driver. The driver may be warned about entered measurements that exceed the numerical limits. Additionally, the measurement information requests that the driver is prompted to enter may be presented to the driver in the order that the measurements should be entered into the trailer backup assist system.

It should be noted that while measurement information is discussed above as being entered by the driver, various methods of entering measurement information may also be employed without departing from the scope of the disclosed subject matter. For example, a system to automatically detect measurements using existing vehicle and trailer data including, but not limited to, vehicle speed, wheel rotation, steering wheel angle, vehicle to trailer relative angle, and a rate of change of the vehicle to hitch angle.

Examples of the measurement information may include a horizontal distance from the rear of the vehicle to the center of a hitch ball, a horizontal distance from the rear of the vehicle to a center of the target, a vertical distance from the target to the ground, and a horizontal offset of the target from a centerline of the hitch ball. In the event the target is attached at other than the centerline of the hitch ball, then the trailer backup assist system must know which side of the vehicle the target is attached to, the passenger side or the driver side. A menu on the HMI may be presented for the driver to indicate passenger side or driver side for the placement of the target. The trailer backup assist system also needs to know the horizontal distance from the rear of the vehicle to a center of the axle or axles of the trailer. The measurements may be entered in either English or metric units.

The driver is presented 622 with the option to revise any of the measurements before proceeding with the setup process. Otherwise, the setup module 600 is complete 624 and the calibration module 700 begins.

The calibration module 700 is designed to calibrate the curvature control algorithm with the proper trailer measurements and calibrate the trailer backup assist system for any hitch angle offset that may be present. After completing the setup module 600, the calibration module begins 700 and the driver is instructed 702 to pull the vehicle-trailer combination straight forward until a hitch angle sensor calibration is complete. The HMI may notify 704 the driver, by way of a pop up or screen display that the vehicle-trailer combination needs to be pulled forward until calibration is complete. When calibration is complete, the HMI may notify 704 the driver. Any hitch angle offset value is stored 706 in memory, accessed as necessary by the curvature control algorithm, and the calibration module 700 ends 704.

It should be noted that while hitch angle calibration is described above as may be requesting the driver pull forward information, various other methods of hitch angle calibration may also be employed without departing from the scope of the embodiment.

Upon completion of the setup module 600 and the calibration module 700, the activation module 800 may begin. The activation module 800 is described with reference to FIG. 11. The activation module 800 is designed to activate automatic steering of the vehicle during trailer backup assist operations. The driver is instructed 802 to place the vehicle in reverse. Upon activation of the trailer backup assist system, the steer-

ing system will not accept any steering angle commands from any source other than the trailer backup assist system 804. The trailer setup 600 and calibration 700 modules must be completed and a current hitch angle must be within a predetermined operating range for the trailer backup assist system 806. The vehicle speed must also be less than a predetermined activation speed 808. In the event any one, or all, of these conditions 804, 806, 808 are not met, the driver is prompted to apply a corrective measure 810. The driver must confirm 814 that the corrective action has been taken in order for the control module to begin. If a corrective action is taken, but the activation module deems it unacceptable, the driver will be instructed 810 to try another corrective action.

For steering systems where the steering wheel is directly coupled to the steered wheels of the vehicle, the driver cannot engage with the steering wheel during trailer backup assist. If any steering wheel motion is obstructed, by the driver or otherwise, the trailer backup assist system will present instructions 810 to the driver to remove their hands from the steering wheel. Activation 800 will be suspended or discontinued until the obstruction is removed. If the vehicle speed exceeds a threshold speed or if the vehicle hitch angle is not acceptable, the driver will be prompted 810 to take corrective action. Until corrective action is taken, accepted and acknowledged, the activation 800 and control 200, 500 modules will be interrupted.

When the driver moves the gear shift from "park" to "reverse" 802 and presses or turns a trailer backup steering input apparatus 125 a rear view camera image may appear in a display of the HMI. If at any time during the reversing process the hitch angle becomes too large for the system to control the curvature of the trailer, the TBA will provide a warning to the driver to pull forward to reduce the hitch angle. If at any time during the reversing process the system is unable to track the hitch angle target, the driver is presented with instructions to correct the problem. If at any time the vehicle speed exceeds that predetermined activation speed, the driver is visually and audibly warned to stop or slow down.

When all of the conditions of the activation module are met and maintained, the control module may begin. The control module executes the directives described above with reference to FIGS. 5 and 7. However, the activation module 800 includes a monitoring function 816 so that, if at any time during execution of the control module 200, 500 the control is interrupted, the driver is instructed to make necessary corrections. In the event any one of the necessary corrections is not made, the control of the vehicle by way of the trailer backup assist system will end. The driver may also intentionally end the control by exiting the system through a menu selection on the HMI or placing the vehicle in a gear setting that is other than park or reverse.

Referring now to instructions processable by a data processing device, it will be understood from the disclosures made herein that methods, processes and/or operations adapted for carrying out trailer backup assist functionality as disclosed herein are tangibly embodied by non-transitory computer readable medium having instructions thereon that are configured for carrying out such functionality. The instructions are tangibly embodied for carrying out the method 200, 500, 600, 700 and 800 disclosed and discussed above and can be further configured for limiting the potential for a jackknife condition such as, for example, by monitoring jackknife angle through use of the equations discussed in reference to FIGS. 5 and 7 and/or by implementing jackknife countermeasures functionality discussed above in reference to FIG. 8. The instructions may be accessible by one or more

data processing devices from a memory apparatus (e.g. RAM, ROM, virtual memory, hard drive memory, etc.), from an apparatus readable by a drive unit of a data processing system (e.g., a diskette, a compact disk, a tape cartridge, etc.) or both. Accordingly, embodiments of computer readable medium in accordance with the disclosed subject matter include a compact disk, a hard drive, RAM or other type of storage apparatus that has imaged thereon a computer program (i.e., instructions) configured for carrying out trailer backup assist functionality in accordance with the disclosed subject matter.

In a preferred embodiment of the disclosed subject matter, a trailer backup assist control module (e.g., the trailer backup assist control module **120** discussed above in reference to FIG. **1**) comprises such a data processing device, such a non-transitory computer readable medium, and such instructions on the computer readable medium for carrying out trailer backup assist functionality (e.g., in accordance with the method **200** discussed above in reference to FIG. **2**) and/or the method **500** discussed above in reference to FIG. **8** and/or the methods **600**, **700** and **800** discussed above in reference to FIGS. **10** and **11**. To this end, the trailer backup assist control module can comprise various signal interfaces for receiving and outputting signals. For example, a jackknife enabling condition detector can include a device providing hitch angle information and hitch angle calculating logic of the trailer backup assist control module. A trailer backup assist control module in the context of the disclosed subject matter can be any control module of an electronic control system that provides for trailer backup assist control functionality in accordance with the disclosed subject matter. Furthermore, it is disclosed herein that such a control functionality can be implemented within a standalone control module (physically and logically) or can be implemented logically within two or more separate but interconnected control modules (e.g., of an electronic control system of a vehicle). In one example, trailer backup assist control module in accordance with the disclosed subject matter is implemented within a standalone controller unit that provides only trailer backup assist functionality. In another example, trailer backup assist functionality in accordance with the disclosed subject matter is implemented within a standalone controller unit of an electronic control system of a vehicle that provides trailer backup assist functionality as well as one or more other types of system control functionality of a vehicle (e.g., anti-lock brake system functionality, steering power assist functionality, etc.). In still another example, trailer backup assist functionality in accordance with the disclosed subject matter is implemented logically in a distributed manner whereby a plurality of control units, control modules, computers, or the like (e.g., an electronic control system) jointly carry out operations for providing such trailer backup assist functionality.

#### Trailer Target Placement and Monitoring

The vehicle trailer backup assist system may utilize a target placed on the trailer to serve as the hitch angle detection component **155**. In doing so, the trailer backup assist system may employ information acquired via image acquisition and processing of the target for use in the hitch angle detection apparatus **130**, according to one embodiment. According to other embodiments, the target may be used to identify if a connected trailer has changed, trailer connection or disconnection, and other trailer related information. The target is an identifiable visual target that can be captured in an image by the video imaging camera and detected and processed via image processing. According to one embodiment, the target may include an adhesive target, also referred to as a sticker, that may be adhered via adhesive on one side onto the trailer, preferably within a target placement zone, such that the cam-

era and image processing may detect the target and its location on the trailer to determine trailer related information, such as the hitch angle between the trailer and the towing vehicle. The trailer backup assist system may provide to the user one or more image(s) of the trailer target zone for proper placement of the target to assist with placement of the target on the trailer. Additionally, the vehicle trailer backup assist system may monitor the target to determine if the target has been correctly placed within a desired target placement zone and provide feedback alert(s) to the user. Further, the trailer backup assist system may monitor the trailer connection by monitoring the target to determine if the target has moved to determine whether the same trailer remains connected to the tow vehicle, and may initiate action in response thereto. Further, the trailer backup assist system may monitor the hitch angle or the target to determine if the trailer may have been changed out (i.e., disconnected and replaced with another trailer), and may initiate action in response thereto.

Referring to FIG. **13**, the vehicle trailer backup assist system **105** is shown including the hitch angle detection apparatus **130** and a target monitor controller **10** for monitoring the target, assisting with placement of the target, monitoring connection of the trailer, determining if the trailer has moved, and initiating certain actions. The target monitor controller **10** may include a microprocessor **12** and/or other analog and/or digital circuitry for processing one or more routines. Additionally, the target monitor controller **10** may include memory **14** for storing one or more routines including image processing routine(s) **16**, a target placement assist routine **900**, a target monitoring routine **920**, an initial setup for target moved detection routine **940**, a target moved detection routine **960**, and a trailer connection monitoring routine **990**. It should be appreciated that the target monitor controller **10** may be a standalone dedicated controller or may be a shared controller integrated with other control functions, such as integrated with the hitch angle detection apparatus **130**, to process the images of the trailer and target and perform related functionality. In one embodiment, the hitch angle detection apparatus **130** processes the acquired images of the target from the target monitor controller **10** and other information such as trailer length for use in determining the hitch angle between the trailer and the towing vehicle.

A camera **20** is shown as an input for providing video images to the target monitor controller **10** of the vehicle trailer backup assist system **105**. The camera **20** may be a rearview camera mounted on the tow vehicle in a position and orientation to acquire images of the trailer towed by the vehicle rearward of the vehicle. The camera **20** may include an imaging camera that generates one or more camera images of the trailer including the region where a target placement zone is expected to be located on the trailer. The camera **20** may include a video imaging camera that repeatedly captures successive images of the trailer for processing by the target monitor controller **10**. The target monitor controller **10** processes the one or more images from the camera **20** with one or more image processing routine(s) **16** to identify the target and its location on the trailer. The target monitor controller **10** further processes the processed images in connection with one or more of routines **900**, **920**, **940**, **960** and **990**.

The trailer monitor controller **10** may communicate with one or more devices including vehicle exterior alerts **24** which may include vehicle brake lights and vehicle emergency flashers for providing a visual alert and a vehicle horn for providing an audible alert. Additionally, the trailer monitor controller may communicate with one or more vehicle human machine interfaces (HMIs) **25** including a vehicle display such as a center stack mounted navigation/entertain-

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ment display. Further, the trailer monitor controller **10** may communicate via wireless communication **22** with one or more handheld or portable devices **26**, such as one or more smartphones. The portable device **26** may include a display **28** for displaying one or more images and other information to a user. The portable device **26** may display one or more images of the trailer and the target location within a desired target placement zone on display **28**. In addition, the portable device **26** may provide feedback information about the vehicle target connection including visual and audible alerts.

Referring to FIGS. **14-17**, the placement of the target **30** onto trailer **110** using the target monitor controller **10** processing the target placement assist routine **900** is illustrated according to one exemplary embodiment. In FIGS. **14** and **15**, a tow vehicle **100** is shown towing a trailer **110**. The trailer **110** has a trailer hitch connector in the form of a coupler assembly **114** connected to a vehicle hitch connector **1416** in the form of a receiver hitch and ball **15**. The coupler assembly **114** latches onto the hitch ball **15** to provide a pivoting ball joint. The trailer **110** is shown having a frame including a longitudinally extending bar or trailer tongue **112**. A top horizontal surface of trailer tongue **112** is shown providing a desired target placement zone **32** for receiving the target **30**. It should be appreciated that the trailer **110** may be configured in various shapes and sizes and may offer one or more other suitable target placement zones **32** for receiving the target **30**. The target placement zone **32** defines the desired location for placement of the target **30**.

The vehicle **100** is equipped with a video imaging camera **20** shown located in an upper region of the vehicle tailgate at the rear of the vehicle **100**. The video imaging camera **20** is elevated relative to the target placement zone(s) and has an imaging field of view and is located and oriented to capture one or more images of the trailer **110** including a region containing one or more desired target placement zone(s). It should be appreciated that one or more cameras may be located at other locations on the vehicle **100** to acquire images of the trailer **110** and the target placement zone(s) **32**.

In order to utilize a target on a trailer that is not currently equipped with a suitable pre-existing target, a user **2** may be instructed or directed to place the target **30** onto the trailer **110** within a desired target placement zone **32** so that the camera **20** may capture one or more images of the target **30** to determine trailer related information for the trailer backup assist system, such as hitch angle information for the hitch angle detection apparatus **130**. In doing so, a user **2** may be prompted by an audible or visual message on an HMI such as the vehicle HMI **25** or portable device **26** to place the target **30** on the trailer **110**. The vehicle HMI **25** may include visual and/or audible outputs generating instructions for proper target placement.

To allow for efficient and proper placement of the target **30** onto the trailer **110**, the trailer backup assist system employs a target placement assist method or routine **900** shown in FIG. **17** that is processed by the target monitor controller **10**. The target placement assist method **900** includes step **902** in which a user may connect a portable device having an image display to communicate with the vehicle. The user may connect the device electronically to the vehicle which can be achieved by way of a wireless protocol, according to one embodiment. The device may be a wireless device that may communicate via Wi-Fi, BLUETOOTH® or other wireless protocol. Alternatively, the device could be connected via a wired connection. Next, at step **904**, the user initiates the hitch angle detection system setup which requires initiating the setup procedure for the hitch angle detection system. As part of this procedure, the user will be required to place a target

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onto the trailer of the vehicle within a target placement zone. At step **906**, the system generates with the camera one or more images of the towed trailer which include a region where the desired target placement zone(s) is expected to be located. There may be more than one target placement zone and one zone may be preferred over another zone. At step **908**, the system processes the generated images and determines the desired target placement zone on the trailer. The desired target placement zone may be determined based on camera location and orientation, desired distance of the target from the hitch connection and the physical structure of the trailer. At step **910**, the system generates a target overlay on the one or more generated images. The target overlay is a visual indication of the desired location of the target within the target placement zone upon which the user is instructed to place the target. The target overlay may include border lines marking the target placement zone or other identifier. The target overlay may be shown by flashing colored (e.g., red) lines on a displayed image. Target overlays of a plurality target placement zones may be generated and shown. At step **912**, the system communicates the one or more images and the target overlay to the vehicle's display and if connected in step **902**, the user's display on the portable device by utilizing the wireless or wired connection. Next, at step **914**, the user's display on the portable device displays an image of the target placement zone indicated by the target overlay. At step **916**, the user is then prompted by an HMI to place the target on the trailer within the target placement zone with assistance from the displayed image and target overlay on the vehicle's display and/or the portable display.

One example of a displayed image on the display **28** of a portable device **26** showing an overlay of the target location for the target to be placed on the trailer is illustrated in FIG. **16**. The image displayed on the display **28** includes an image of the trailer **110** as captured by the camera and further includes an overlay of the desired target placement zone **32**. The user **2** may view the image on the display **28** of the portable device **28** to determine where to place the target relative to the trailer **110**. In this example, the user may place the target **30** onto the target placement zone **32** as indicated by the target overlay. Placement of the target may be achieved by adhering a target sticker onto a surface of the trailer. As a result, the user may employ a portable device with a display, such as a phone, a tablet, or a computer to view the proper location for placement of the target on the trailer prior to and during application of the target onto the trailer.

Accordingly, the target placement assist method **900** advantageously assists the user with placement of the target **30** onto the trailer **110** in a manner that is simple to use, accurate and efficient. The user **2** may easily transport a portable device having a display to communicate with the vehicle and view the correct placement location for the target prior to and during the target placement procedure without having to return to the vehicle or otherwise be prompted for target placement.

The trailer backup assist system **105** further includes a target monitoring method or routine for monitoring placement of the target on the trailer and providing feedback to the user as to whether the target has been placed within a proper target placement zone. A user may place a target on the trailer in various ways. In some situations, the user may be prompted by the TBA system via a vehicle HMI to place a target on the trailer and may be given instructions as to the location. The user may employ the target placement assist method **900** to assist with placement of the target on the trailer. In other situations, the user may place the target on the trailer using their best judgment or following instructions printed on the

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target or packaging provided therewith. In any event, once the target is placed on the trailer, the target monitoring method 920 will monitor the location of the target relative to the trailer and provide feedback to the user as to correct or incorrect placement of the target on the trailer.

The target monitoring method 920 is illustrated in FIG. 18, according to one embodiment. At step 922, method 920 requires attaching the trailer to the vehicle onto the ball and hitch if it is not already attached. Next, at step 924, setup for the hitch angle detection is initiated. At step 926, the user is prompted via an interface to place the target on the trailer. The user may place a target on the trailer based on predefined criteria or the user's best judgment or knowledge, according to one embodiment. The user may be instructed on where to place the target on the trailer by use of a user's manual, an instruction sheet, or other visual or audible communication of instructions, according to other embodiments. Generally, the target should be placed in a region that is unobstructed from view by the camera and that allows for the acquisition of an image and determination of desired trailer related information, such as the hitch angle. Depending on the trailer configuration and camera orientation and height, the target may be required to be placed within a certain region of the trailer, within a distance range from the trailer hitch connection having a minimum distance from the hitch connection, such as 7 inches (17.78 centimeters), within a range from the tow vehicle bumper, and within a range of height from the ground. The target placement may require a location within a certain distance from a centerline of the longitudinal axis of the trailer, and may require a vertical or horizontal angle or some angle in between the vertical and horizontal positions. According to another embodiment, the user may utilize the target placement assist method 900 to place the target on the trailer.

At step 928, the system generates one or more images of the target placement zone on the towed trailer. The system then processes the one or more images to determine the presence of a target within a desired target placement zone at step 930. The desired target placement zone may be determined by criteria, such as distance from the trailer hitch connection formed by the coupler assembly 114, distance from a centerline of the longitudinal axis of the trailer, height of the camera relative to the trailer, and distance of the camera from the trailer. At decision step 932, method 900 determines if the target has been detected by the processed image(s) and, if not, returns to step 926 to prompt the user via an HMI to place the target on the trailer.

If the target has been detected by the processed images, the vehicle trailer backup assist system provides a feedback alert to the user at step 934. The feedback alert may include one or more of vehicle exterior alerts including visual alerts, such as flashing the vehicle brake lights and/or flashing the vehicle emergency flashers, and/or audible alerts, such as sounding the vehicle horn. Additionally, the feedback alerts may include providing a message via the portable device 26, providing an audible tone via the portable device 26 or a visual lighted indication via the portable device 26. Further, feedback alerts may include sending a text message or audible instructions to a user via a portable device, such as a phone or computer. It should be appreciated that other vehicle exterior and alternative feedback alerts may be communicated to the user to indicate that proper placement of the target has been detected on the trailer. Alternatively, the feedback alerts could be used to indicate improper placement of the target on the trailer. Once the trailer is properly equipped with the target in the proper location, the trailer backup assist system may

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process information by monitoring the target to determine the hitch angle and other trailer towing related functionality.

The target 30 may include a sticker having adhesive on the bottom surface and a predetermined image pattern of a certain size and shape provided on the top surface for capture by the video camera and recognition by the image processing. The target 30 may have a rectangular shape, according to one embodiment, and may have a camera image recognizable pattern such as the checker pattern shown. The image processing may include known image pattern recognition routines for identifying a target pattern and its location on a trailer. However, it should be appreciated that other target shapes, sizes and patterns may be employed. It should further be appreciated that the target may otherwise be connected to the trailer using connectors, such as fasteners, which may connect to the trailer or to an attachment to the trailer. It should further be appreciated that the target can be attached via magnet, glued on, painted on, or any number of other suitable means.

It should be appreciated that not all trailers are necessarily configured to provide a well-suited location for placement of a target sticker on the trailer. Accordingly, a target location may be added to a given trailer by use of a target mounting system 40 as shown in FIGS. 19 and 20, according to one embodiment. The target mounting system 40 is shown installed onto trailer 110 to present a target 30 that is viewable by the camera within a desired target placement zone. The target mounting system 40 includes a vertical mounting post or bracket 44 having a plurality of bolt receiver holes 46 extending vertically to allow for a desired vertical height adjustment. The bracket 44 may be assembled onto the trailer via holes 54 using bolts 48, washers 52 and nuts 50. The height of the bracket 44 may be adjusted depending on which holes 46 are aligned with the trailer holes 54. Mounted to the top of the bracket 44 is a target plate 42 having a top target placement zone 32 onto which the target 30 is located. The plate 42 likewise has a plurality of holes 46 that align horizontally with the holes in the bracket 44 and may be assembled thereto via bolts 48, washers 52 and nuts 50. Accordingly, the plate 42 may be adjusted both vertically and horizontally to a desired position so as place the target 30 adjustably within a desired location so that the target is easily acquired by the camera and processed by the image processing. It should be appreciated that assistance in mounting the target mounting system 40 along with the target 30 and verification of proper location of the target mounting system 40 and target 30 may be achieved by utilizing the target placement assist method 900 and target monitoring method 920 discussed above.

The target moved detection method includes an initial setup routine 940 and subsequent processing routine 960 for target moved detection used for prompting the entry of trailer information. The target moved detection method determines if the location of a hitch angle target on a trailer, such as a trailer tongue, has moved and may also determine if the distance has changed. Images of the target in a previously stored image and a newly acquired image are compared to determine if the location and/or distance to the target has changed. The comparison may include comparing camera image pixel sizes of the images. If either the location or the distance changes, the user is then prompted by an HMI to reenter new trailer information for subsequent processing of the trailer backup assist system.

The initial setup routine 940 is illustrated in FIG. 21. Initially, the trailer must be attached to the vehicle at step 942. At step 944, the attached trailer is setup for hitch angle tracking. For a vision-based system, this may include applying a target

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sticker to the trailer, such as in the vicinity of the tongue of the trailer, so that the vehicle-based camera can detect motion of the target as the trailer maneuvers and swings around curves. In addition, a number of parameters associated with the location of the target that are used to properly calculate the hitch angle based on the vision processing may be entered. These parameters may include the distance of the target to the ground and the distance from the target to the bumper of the vehicle. At step 946, the vehicle and the trailer are directed to be driven straight, which may be achieved by driving the vehicle and towed trailer in the forward direction. This is to ensure that there is about zero hitch angle between the vehicle and trailer with the trailer in-line with the vehicle and that the image generated in subsequent steps will be taken in the same orientation and will be valid for image comparisons. At step 948, a picture (image) of the target and trailer are acquired with the use of the camera while the vehicle and the trailer are in a straight line at a hitch angle of about zero degrees. At step 950, the image processing performs vision processing on the image. The vision processing may first detect a target and then compute the size and location of the target based on processing the pixels of the image. At step 952, the image acquired in step 948 is stored in memory and the information calculated in step 950 is stored in memory. The image and calculated information are then subsequently used to determine if the target has moved. If the target has moved, the system may assume that the trailer may have been changed or replaced with a different trailer, and hence prompts the user via an HMI to enter trailer information.

Referring to FIG. 22, the target moved detection routine 960 is shown beginning at step 962 in which the driver is instructed to reattach to the vehicle a trailer that was previously set up and used in the initial setup routine 940. At step 964, the user is prompted by the hitch angle detection system to select the trailer that was previously setup and stored, rather than selecting a new trailer. At step 966, the user is prompted to drive the trailer and vehicle combination forward in a straight line to achieve a hitch angle of about zero degrees. Next, at step 968, a new image of the target and the trailer are acquired by the camera. At step 970, vision processing is performed on the image to detect the target and compute the size and location of the target by processing the pixels of the image. At step 972, the target location and size as calculated above are compared to the location and size of the target taken in the prior image from the initial setup. At step 974, a determination is made to determine if the new target information is a match or within tolerance of the original target information. If the newly acquired target is still a similar size and in the similar location on the image as compared to the prior image from the initial setup, then the target is likely to be in the same location and will allow for a proper hitch angle detection if determination of such is made in step 980. If the target has a different location or has a different size, then the target is presumed to have moved and routine 960 proceeds to step 976. Detected movement of the target may occur when the trailer is a different trailer as compared to the trailer last selected by the user. The use of the prior selected trailer configuration may provide erroneous results for hitch angle target tracking. As such, method 960 proceeds to step 978 to prompt the user (e.g., driver) to reselect or re-setup the trailer configuration with new target and trailer information. Accordingly, the target moved detection routine 960 advantageously detects movement of the target which may indicate potential connection of a new trailer to the vehicle, such that the user is prompted via an HMI to select new trailer configuration information. Additionally, the target moved routine

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could also detect that a target has moved due to a different sized drawbar being installed than what was installed when the trailer was initially setup.

Examples of images of the trailer and the target moved to a different position are illustrated in FIGS. 23A and 23B. As shown in FIG. 23A, an image of the trailer and the target 30 is shown aligned on the trailer in a first position as compared to the subsequent image in FIG. 23B showing the target 30 moved to a new second closer position. The change in location of the target may be an indication that the trailer has been changed out with a new trailer or that the target has otherwise been moved on the trailer. When this occurs, the target move detection routine 960 requires the user to re-enter trailer configuration information so that the wrong information is not used to provide incorrect hitch angle data. Furthermore, it is possible that the right (correct) trailer has been selected and the target is still in the same location on the trailer, but the system still indicates that the target has moved. This could occur if the drawbar length on the vehicle has changed.

Target monitor controller 10 further processes a trailer connection monitoring routine 990 to determine whether a trailer is connected to the vehicle and whether a new trailer may have been connected. When the trailer is disconnected from the vehicle, the target information and the hitch angle information may be unavailable for a period of time. Accordingly, the trailer connection monitoring method 990 monitors the availability of the hitch angle data and/or the detection of the target to determine if the hitch angle data or target data is lost for a substantial period of time. If this occurs, the driver is then prompted via an HMI to reselect the attached trailer or to re-enter trailer configuration data to ensure that the wrong trailer information is not employed.

The trailer connection monitoring routine 990 is illustrated in FIG. 24. At step 992, a trailer is connected to the vehicle. At step 994, the trailer is setup for hitch angle detection and monitoring. If a vision based system is employed, this may include placing a target on the trailer for the vision-based system to detect as well as entering pertinent parameters. Alternatively, if the trailer has been previously setup for hitch angle monitoring, it may be possible to select the previously stored setup configuration for that trailer. At step 996, once the trailer has been setup for hitch angle detection, the hitch angle detection system will continuously monitor the hitch angle or target. At decision step 998, routine 990 determines if the hitch angle or the target has been dropped for a time period greater than X seconds.

Depending on the type of hitch angle system, the hitch angle signal may drop or become unavailable for different reason, but one potential reason is that the trailer has been disconnected from the vehicle. A disconnected trailer may also result in the target detection being unavailable. As such, a check is made to see how much time has expired since the hitch angle signal or target detected has been dropped. If the hitch angle or target detection has been dropped for a time period of less than X seconds, then routine 990 returns to track the hitch angle or target at step 996. If the hitch angle or target detection has been dropped for a time period greater than X seconds, then the user is prompted via an HMI to reselect or re-setup the trailer configuration in step 1000. The time period X is set to represent a reasonable amount of time needed to swap or change-out trailers. For example, for extremely small, lightweight trailers, it may be possible to swap trailers out in less than sixty (60) seconds, so this could be a reasonable time period. According to one embodiment, the time period X is set for thirty (30) seconds.

While the hitch angle is monitored to determine disconnection of a trailer from the vehicle, it should be appreciated

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that the trailer connection monitoring routine **990** may monitor detection of the target as an alternative, such that if the target is no longer detected for X seconds, then the vehicle driver may be prompted to reselect or reconfigure the trailer.

#### Supplemental Vehicle Lighting System

As previously described, the trailer backup assist system **105** may employ a vision based target detection system, wherein the hitch angle detection component **155** is an identifiable visual target located on a trailer attached to a towing vehicle. The towing vehicle may be equipped with a rear view camera, which functions as the hitch angle detection apparatus **130**, and is configured to image the target and process acquired image data to generate trailer related information used in a variety of applications associated with the trailer backup assist system **105**. By following the previously described target placement assist method **900** and/or other suitable methods, a vision based target detection system can be readily configured for accurate target detection. Nevertheless, there may be some circumstances that hinder target detection accuracy. One such circumstance involves performing target detection under dark conditions when existing vehicle lights, such as taillights, provide insufficient target lighting. While aftermarket lighting assemblies are available, such assemblies may appear unsightly and may lack the ability to be integrated with the trailer backup assist system **105**. Thus, it is desired to provide a supplemental vehicle lighting system that not only cooperates with the trailer backup assist system **105**, but also confers a styling advantage to vehicles in which it is featured.

As will be described in greater detail below, a supplemental vehicle lighting system is disclosed herein that utilizes an existing keylock hole of a rear vehicle closure member or other rear vehicle fixture. For purposes of illustration, FIG. **25A** exemplarily shows a tow vehicle **1005** having a rear vehicle closure member embodied as a tailgate **1010** that includes a keylock hole **1015** defined in a tailgate handle assembly **1020**. As exemplarily shown in FIGS. **25B-25D**, the keylock hole **1015** is customarily used in conjunction with a corresponding keylock cylinder **1025** that includes a keyhole **1030** that is accessible through the keylock hole **1015**. It should be appreciated that the keylock cylinder **1025** may be supported inside the tailgate **1010** in a variety of ways. For purposes of illustration, the keylock cylinder **1025** is shown engaged to protrusions **1035**, **1038**, and **1040** of the tailgate handle assembly **1020** and is secured to the tailgate handle assembly **1020** with mechanical fastener **1045**. When a corresponding key is inserted into the keyhole **1030** and turned in the proper direction, a locking tab **1050** of the keylock cylinder **1025** is moved to an unlocked position to enable the tailgate **1010** to be lowered so that a rear vehicle cargo area can be accessed. While the rear closure member has been generally described herein as a tailgate **1010**, it should be appreciated that the rear closure member may also include a liftgate, a trunk lid, a swing door, a sliding door, and the like, depending on the type and/or make of the selected vehicle **1005**. Likewise, it should also be appreciated that the configuration and/or location of the keylock hole **1015** and keylock cylinder **1025** may vary across vehicle types and/or makes. Therefore, the keylock hole **1015** may be defined in other parts and/or areas of the rear vehicle closure member or in some other rear vehicle fixture altogether.

While many current vehicles are equipped with a keylock hole and a keylock cylinder, seldom is a key used to unlock a rear vehicle closure member given the proliferation of vehicles having power lock systems or other means of entry. Thus, with respect to some vehicles, the inclusion of a keylock cylinder produces added cost and consumes space that

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could otherwise be used to implement other devices. Recognizing this, a supplemental vehicle lighting system is provided herein that advantageously replaces a keylock cylinder with a light assembly operably coupled to a rear keylock hole of a selected vehicle, through which the light assembly is able to illuminate a rear vehicle area. In so doing, little to no modification need be made to existing rear vehicle fixtures since the light assembly may be fashioned to be mounted to in the same way as the keylock cylinder. In this manner, vehicle manufacturers can offer vehicles equipped with a light assembly without having to perform substantial retooling. Similarly, an existing keylock cylinder may be easily swapped for a light assembly in vehicles desiring the benefits bestowed by the supplemental vehicle lighting system described herein.

Referring to FIGS. **26A-26D**, a light assembly **1055** is shown according to one embodiment and includes a housing **1060** having an open top defined by an upper edge **1065**. The light assembly **1055** also includes a barrel **1070** having a distal end **1075** and a proximal end **1080**. A lighting device **1085** including one or more light emitting diodes (LEDs) **1087** is disposed inside the housing **1060** and is configured to emit light through the barrel **1070** beginning from the proximal end **1080**. The barrel **1070** may be constructed from a reflective material to trap the emitted light inside the barrel **1070** as it propagates towards the distal end **1075** of the barrel **1070**. The emitted light is then dispersed from the barrel **1070** via a lens **1090** that is coupled to the distal end **1075** of the barrel **1070**.

In the illustrated embodiment, the lens **1090** includes a first section **1091**, a second section **1092**, and an intermediate section **1093** therebetween. The second section **1092** is configured to be inserted into the barrel **1070** through the distal end **1075** such that the intermediate section **1093** abuts against the distal end **1075** and may be adhered thereto using an adhesive. In this arrangement, the first section **1091** is most distal to the lighting device **1085**. Additionally, the first section **1091** may be curved and optically configured to disperse the emitted light in a variety of directions including a forward, upward, downward, and/or sideways direction.

As best shown in FIGS. **26C** and **26D**, the lighting device **1085** has an L-shaped configuration and is electrically coupled to an electrical connector **1095** provided at the bottom of the housing **1060**. The lighting device **1085** includes a first end **1097** that abuts against the proximal end **1080** of the barrel **1070** and supports a heat sink board **1100** on which the LEDs **1087** are mounted. The lighting device **1085** also includes a plug **1102** disposed at a second end having pins **1107** that plug into a corresponding socket **1109** of the electrical connector **1095**. To supply power to the lighting device **1085**, the electrical connector **1095** may be configured to make an electrical connection with an onboard vehicle power source or other power source.

To assist the heat sink board **1100** with heat dissipation, the light assembly **1055** may include a heat management member **1115** positioned proximate to the lighting device **1085**. The heat management member **1115** may be a straight heat sink (as shown), or other heat sink type, such as, but not limited to, a pinned heat sink or a flared heat sink, and may be mounted to the upper edge **1065** of the housing **1060** via threaded fasteners **1120**. Optionally, a thin plate **1122** may be provided for distributing the load of the threaded fasteners **1120**. As shown in FIG. **26C**, the thin plate **1122** is contiguous with the upper edge **1065** of the housing **1060** and is disposed between the upper edge **1065** of the housing **1060** and the heat management member **1115**.

Referring to FIGS. **27A** and **27B**, the light assembly **1055** is exemplarily shown mounted to the tailgate handle assem-

bly 1020 previously shown in FIGS. 25A-25D. The light assembly 1055 is configured to be engaged to protrusions 1035, 1038, and 1040 and is secured to the tailgate handle assembly 1020 with mechanical fastener 1045 to mirror the mounting scheme of the keylock cylinder 1025 previously shown in FIG. 25D. In this manner, the keylock cylinder 1025 and light assembly 1055 are easily interchanged. However, it should be appreciated that other mounting schemes may be employed for mounting the light assembly 1055 to the tailgate handle assembly 1020 or other rear vehicle fixture. With respect to the presently illustrated embodiment, mounting of the light assembly 1055 to the tailgate handle assembly 1020 results in the intermediate section 1093 of the lens 1090 abutting against an interior surface 1125 of the tailgate handle assembly 1020. In this arrangement, the barrel 1070 is concentrically aligned with the keylock hole 1015 such that the first section 1091 of the lens 1090 at least partially coincides with the keylock hole 1015 while the tailgate handle assembly 1020 shields the rest of the light assembly 1055. Once the light assembly 1055 is secured, an electrical connection may be made between the electrical connector 1095 of the light assembly 1055 and a plug 1127 stemming from an onboard vehicle power supply or other power source such that power may be supplied to the lighting device 1085.

In operation, the lighting device 1085 may be activated using a variety of means. For example, the lighting device 1085 may be manually activated via a user input mechanism, such as a button located on a human machine interface (e.g. HMI 102), or elsewhere in the selected vehicle. Additionally, or alternatively, the lighting device 1085 may be automatically activated via an onboard vehicle system such as the trailer backup assist system 105 and/or other vehicle system. For instance, when performing a backup maneuver, the trailer backup assist system 105 may activate the lighting device 1085 under dark conditions. In another instance, the lighting device 1085 may be automatically activated during set up of the trailer backup assist system 105, as described previously in step 604 of FIG. 10.

Referring to FIG. 28, a supplemental vehicle lighting system 1130 is implemented in the vehicle 1005 previously shown in FIG. 25A. For purposes of illustration, the vehicle 1005 features the trailer backup assist system 105 and employs vision based target detection. As shown, the vehicle 1005 is attached to a trailer 1135, which may be variously configured and may offer one or more suitable target placement zones for receiving a target 1140. In the illustrated embodiment, the target 1140 is placed on a trailer tongue 1145 of the trailer 1135 and is imaged by a rear view camera 1150 mounted in an upper region of the tailgate 1010. By virtue of its positioning in the tailgate 1010, the rear view camera 1150 is shown imaging a scene 1155 that is to the rear of the vehicle 1005 and points slightly downwards therefrom so that the target 1140 is present in the scene 1155. To assist the camera 1150 in accurately imaging the target 1140 in dark conditions, the light assembly 1055 described previously herein is mounted inside the tailgate 1010 and is operable to illuminate a rear vehicle area 1160 that includes the target 1140 and at least partially overlaps with scene 1155. With respect to the illustrated embodiment, it can be seen that the rear vehicle area 1160 can include the area behind a rear bumper 1165 of the vehicle 1005. Since the keylock hole 1015 is defined in the tailgate handle assembly 1020, the light assembly 1055 may be mounted to the tailgate handle assembly 1020 in the manner described in reference to FIG. 27A or other suitable manner.

Although the supplemental vehicle lighting system 1130 has been described herein as being featured in a tow vehicle

1005 generally embodied as a pickup truck, it should be appreciated that the supplemental vehicle lighting system 1130 may be featured in other tow and non-tow vehicles alike, which may include, but are not limited to, buses, sports utility vehicles, vans, station wagons, sedans, and coupes. Furthermore, while the supplemental vehicle lighting system 1130 is intended for use with the trailer backup assist system 105, it should be appreciated that the vehicle lighting system 1130 may additionally, or alternatively, be adapted for use with other vehicle related applications. For example, the additional lighting provided by the light assembly 1055 will enable a vehicle equipped with a rear view camera system to render clearer images on a display screen when it's dark outside. This may prove especially useful when performing a backup maneuver in low visibility situations. At the most basic level, the supplemental vehicle lighting system 1130 may simply be used as a utility light. For example, the light assembly 1055 may be activated to aid an operator with attaching/detaching a trailer to/from a tow vehicle in low light conditions.

#### Secondary Hitch Angle Sensor System

For the trailer backup assist system 105, as previously described, it is advantageous to use information that is representative of an angle between the vehicle and a trailer attached to the vehicle, also known as the hitch angle  $\gamma$  or trailer angle. In addition to the trailer backup assist system 105, it is contemplated that other vehicle systems may utilize hitch angle information as an input to the system, whereby the hitch angle information may be manipulated by a controller or microprocessor associated with the vehicle 100. In some embodiments, a measured hitch angle  $\gamma(m)$  may not provide an accurate measurement of the actual hitch angle  $\gamma(a)$  to a requesting system, which may introduce a potential for inadequate or improper vehicle system control, especially in situations where the hitch angle information may be important to the vehicle system being controlled, such as the trailer backup assist system 105. Furthermore, as previous mentioned, the hitch angle signal may drop-out or become unavailable for different reasons, such as the hitch angle detection apparatus 130 momentarily being unable to sense the relative position of trailer 110, or more specifically, the camera 20 being unable to track the hitch angle target 30 or other hitch sensors, such as a potentiometer, magnetic, optical, or mechanical based sensors, being unable to provide a constant hitch angle measurement, which may similarly cause errors or other disruption in operating the trailer backup assist system 105. Accordingly, an accurate and consistent estimate of the actual hitch angle  $\gamma(a)$  is desired, including for a means to confirm the accuracy of a measured hitch angle  $\gamma(m)$ .

Referring to FIGS. 29-31, a sensor system 1200 for estimating a hitch angle of a trailer 110 attached to a vehicle 100 is shown according to one embodiment, which includes a primary sensor 1202 having a camera 20 monitoring a target 30 on the trailer 110 to determine a measured hitch angle  $\gamma(m)$  and a secondary sensor 1204 that monitors the trailer 110 to determine an indicator 1206 of the actual hitch angle  $\gamma(a)$ . In this embodiment, the trailer backup assist system 105 operates the vehicle 100 when the measured hitch angle  $\gamma(m)$  correlates with the indicator 1206 of the actual hitch angle  $\gamma(a)$ . This and other embodiments of the sensor system 1200 are described in more detail below.

In the embodiment illustrated in FIG. 29, the vehicle 100 is a pickup truck that employs vision based target detection as the primary sensor 1202 to determine the measured hitch angle  $\gamma(m)$ . Accordingly, the primary sensor 1202 on the vehicle 100 includes a hitch angle detection apparatus 130 that has a camera 20 as an input for providing video images to a target monitor controller 10 of the primary sensor 1202. The



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camera **20** (e.g. video imaging camera) is located proximate an upper region of the vehicle tailgate at the rear of the vehicle **100**, such that the camera **20** is elevated relative to the target placement zone(s) and has an imaging field of view located and oriented to capture one or more images of the trailer **110**, including a region containing one or more desired target placement zone(s) **32**. It should be appreciated that the camera **20** may include one or more video imaging cameras and may be located at other locations on the vehicle **100** to acquire images of the trailer **110** and the desired target placement zone(s) **32**.

As also shown in FIG. **29**, the tow vehicle **100** is pivotally attached to one embodiment of a trailer **110**. The trailer **110** has a trailer hitch connector in the form of a coupler assembly **114** connected to a vehicle hitch connector **1416** in the form of a receiver hitch and ball **15**. The coupler assembly **114** latches onto the hitch ball **15** to provide a pivoting ball joint connection **117**. The trailer **110** is shown having a frame **1208** that includes a longitudinally extending bar or trailer tongue **112** that is coupled with opposing front frame members **1210** that angle laterally away from the trailer tongue **112** and extend rearward to couple with side frame members **1212** that extend longitudinally in parallel alignment and are supported by a rotatable wheel axle **1214** of the trailer **110**. The forward facing surfaces of the trailer frame **1208**, including the trailer tongue **112** and the front and side frame members, **1210**, **1212** provide surfaces for the secondary sensor **1204** to monitor the position of the trailer **110**. Again, it should be appreciated that the trailer **110** may be configured in various shapes and sizes, may include more than one axle, and may have additional or alternative surfaces for the secondary sensor **1204** (FIG. **30**) to monitor.

With further reference to FIG. **29**, the vehicle **100** has additional onboard proximity sensors, including but not limited to, a reverse aid system **1220**, a blind spot system **1216**, and a cross traffic alert system **1218**. In one embodiment, the reverse aid system **1220** includes a pair of energy transducers coupled with the rear of the vehicle **100** below the vehicle tailgate on opposing sides of the pivoting ball joint connection **117** between the vehicle **100** and the trailer **110**. The energy transducers of the reverse aid system **1220**, in the illustrated embodiment, comprise ultrasonic sensors that are directed rearward in the general vicinity of the trailer **110** for monitoring the position of the trailer **110** by measuring a difference in return signals from the ultrasonic sensors on opposing sides of the pivoting ball joint connection **117**. The difference in the return signals is used to determine the indicator **1206** (FIG. **30**) of the actual hitch angle  $\gamma(a)$ . The indicator **1206** may be a second measured hitch angle  $\gamma(m2)$ , which can be used to define an acceptable tolerance range of hitch angles. The indicator **1206** may also be another conceivable type of indicator, as described in further detail herein. The reverse aid system **1220** may include additional sensors, including other types of sensors, such as radar sensors, located at several locations at the rear of the vehicle **100**, such as laterally spaced along the bumper.

The blind spot system **1216**, according to one embodiment shown in FIG. **29**, includes an energy transducer **1222** coupled with each of the side rear view mirrors that generate a sensor field adjacent to the sides of the vehicle **100** and rearward therefrom in the general vicinity of the trailer **110**. The energy transducers **1222** of the blind spot system **1216** may be ultrasonic sensors that monitor the general position of the trailer **110** to determine an indicator **1206** of the actual hitch angle  $\gamma(a)$ . Accordingly, it is conceivable that the blind spot system **1216** may be used to determine when the trailer **110** is roughly centered behind the vehicle **100** or in line with

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the vehicle **100** when the return signals from both energy transducers **1222** are both low and/or relatively equal. Also, the blind spot system **1216** may provide an indicator **1206** (FIG. **30**) of the actual hitch angle  $\gamma(a)$  based on the magnitude of return signal from the respective energy transducer **1222** receiving the greater return signal. For instance, a set of ranges of ascending magnitudes may be set to correspond with a general hitch angle (e.g. 10-20 Hz for 5 degrees, 20-30 Hz for 10 degrees, etc.) or ranges of hitch angles (e.g. 0-40 degrees, 40-70 degrees, 70-100 degrees), such that the return signal may be an indicator **1206** (FIG. **30**) of the actual hitch angle  $\gamma(a)$  for use with the sensor system **1200** or for use as a primary sensor **1202** in an alternative embodiment.

The cross traffic alert system **1218**, as shown in FIG. **29**, also incorporates energy transducers **1224** on the rear of the vehicle **100** to generate sensor fields for monitoring the general position of the trailer. Specifically, the cross traffic alert system **1218** in the illustrated embodiment includes energy transducers **1224** comprising a pair of ultrasonic sensors directed rearward and laterally outward from the rear of the vehicle **100**, such that the ultrasonic sensors may determine when the trailer **110** has reached a large hitch angle or is approaching a critical angle indicative of a jackknife condition or jackknife angle  $\gamma(j)$ . In addition, the secondary sensor **1204** may comprise an auxiliary hitch angle sensor **1226** (FIG. **30**) attached to the trailer **110** and/or the vehicle **100**, such as mechanical sensor mechanisms or other conceivable hitch angle sensors. It is also contemplated that any of the onboard proximity sensors (FIG. **32**), including, but not limited to, the reverse aid system **1220**, blind spot system **1216**, the cross traffic alert system **1218**, and the auxiliary sensor **1226**, may have an ultrasonic sensor, a radar sensor, or a combination of the two. These secondary sensors **1204** for determining the position of the trailer **110** may also include other cameras located on the vehicle, cameras located on the trailer, or other sensing devices generally understood by one having ordinary skill in the art. It is also conceivable that more than one onboard sensor system may be incorporated into the secondary sensor **1204**, offering multiple individual sensors that contribute to the indicator **1206** of the actual hitch angle  $\gamma(a)$ .

Referring to FIG. **30**, the sensor system **1200** of the trailer backup assist system **105** (FIG. **1**) has the primary sensor **1202** for determining a first measured hitch angle  $\gamma(m)$  and the secondary sensor **1204** for determining an indicator **1206** of the actual hitch angle  $\gamma(a)$ , such as a second measured hitch angle  $\gamma(m2)$ . In one embodiment, the secondary sensor **1204** may be used in place of the primary sensor **1202** when the signal of the first measured hitch angle  $\gamma(m)$  becomes unavailable or unreliable, thereby using the second measured hitch angle  $\gamma(m2)$  in place of the first measured hitch angle  $\gamma(m)$ . Additionally or alternatively, the secondary sensor **1204** may be used in conjunction with the primary sensor **1202** to confirm that the first measured hitch angle  $\gamma(m)$  correlates with the indicator **1206** of the actual hitch angle  $\gamma(a)$ . In one embodiment, as described above, the primary sensor **1202** may include the hitch angle detection apparatus **130** and the target monitor controller **10** for monitoring the target **30** on trailer **110** to determine the first measured hitch angle  $\gamma(m)$ . The secondary sensor **1204** includes a trailer monitoring apparatus **1228** and a trailer monitoring controller **1230** for monitoring the trailer **110** to determine the indicator **1206** of the actual hitch angle  $\gamma(a)$ . The trailer monitoring controller **1230** may include a microprocessor **1232** and/or other analog and/or digital circuitry for processing one or more routines. Also, the trailer monitoring controller **1230** may include memory **1234** for storing one or more routines including



sensor signal processing routines **1236** and hitch angle confirmation routines **1238**. It should be appreciated that the trailer monitoring controller **1230** may be a standalone dedicated controller or may be a shared controller integrated with other control functions, such as integrated with the trailer monitoring apparatus **1228** and/or the primary sensor **1202**, to process the return signals of the onboard proximity sensors or other secondary sensors and perform related functionality.

The trailer monitoring controller **1230** illustrated in FIG. **30** receives and processes return signals from at least one of the camera **20**, the blind spot system **1216**, the reverse aid system **1220**, the cross traffic alert system **1218**, and the auxiliary hitch angle sensor **1226**, which may include additional processing from the trailer monitoring apparatus **1228**. The secondary sensor **1204** processes the return signals to determine the indicator **1206** of the actual hitch angle  $\gamma(a)$ , such as using the reverse aid system **1220** to determine a second measured hitch angle  $\gamma(m2)$  as the indicator **1206** and/or using the blind spot system **1216** to determine a range of hitch angles as the indicator **1206**. The hitch angle confirmation routine **1238** further processes the indicator **1206** in connection with the first measured hitch angle  $\gamma(m)$  to determine if the first measured hitch angle  $\gamma(m)$  correlates with the indicator **1206**. For instance, the indicator **1206** may include the second measured hitch angle  $\gamma(m2)$  that defines a tolerance range of acceptable hitch angles (e.g.  $\pm 3$  degrees of the second measured hitch angle, or a wider or narrower tolerance range), such that the first measured hitch angle  $\gamma(m)$  correlates with the indicator **1206** when the first measured hitch angle  $\gamma(m)$  is within the tolerance range. It is contemplated that in one exemplary embodiment, the hitch angle confirmation routine **1238** may also process the first measured hitch angle  $\gamma(m)$  to define an average measurement thereof over an interval of time (e.g. 2 seconds, or a longer or shorter interval) to reduce instability and variance of the first measured hitch angle  $\gamma(m)$ .

As also illustrated in FIG. **30**, the sensor system **1200** may communicate with one or more devices including, the vehicle HMI **25**, the vehicle exterior alerts **24**, and the vehicle interior alerts **1240**, which may include a blind spot indicator light **1242** that provides a visual alert. It is contemplated that the blind spot indicator light **1242** may be on an interior or exterior of the vehicle **100**, such as on or proximate a side rear view mirror, to alert the driver that the primary sensor **1202** does not correlate with the indicator **1206** of the actual hitch angle  $\gamma(a)$ , the trailer **110** is approaching or is in a jackknife condition, or other conceivable warnings that may not be able to be displayed on the center stack screen when reversing the vehicle **100**. Additional warnings that may be provided with the blind spot indicator light **1242** include overspeed warning that alerts the driver that they are approaching a speed greater than the speed configured for operating the trailer backup assist system **105**, a steering override warning that alerts the driver that steering has exceeded the acceptable steering torque configured for operating the trailer backup assist system **105**, or an internal fault warning that alerts the driver that the trailer backup assist system **105** has become inoperative and has to canceled out for other conceivable errors. As previously described, the sensor system **1200** may communicate via wireless communication **22** to various types of mobile devices or via onboard communication to one or more vehicle human machine interfaces (HMIs) **25**, including a vehicle display, such as a center stack mounted navigation/entertainment display.

The method for estimating the actual hitch angle  $\gamma(a)$  using the sensor system **1200** of the trailer backup assist system **105** is illustrated in FIG. **31** according to one embodiment. Ini-

tially, at step **202** the system may receive an initiation request to activate the trailer backup assist system **105** for tracking the hitch angle. Before proceeding to monitor the hitch angle, at step **1244** the system confirms that the attached trailer **110** has been calibrated and setup for operation with the trailer backup assist system **105**, and if not, the calibration and setup process **600**, **700** are initiated, as previously described. Although the calibration and setup processes **600**, **700** may involve gathering the kinematic information for the attached trailer **110**, at step **1246**, the sensor system receives this information for use with the primary and/or secondary sensors **1202**, **1204**, if necessary. For instance, if a vision based target detection system is included as the primary sensor **1202**, the kinematic information will provide parameters from the target setup information in addition to the input or otherwise determined dimensions of the trailer **110**. The trailer kinematic information may also be used by the sensor system **1200** to modify the tolerance range of acceptable first measured hitch angles and to modify the magnitudes of sensor return signals or corresponding ranges of hitch angles.

Still referring to FIG. **31**, once the trailer backup assist system **105** is generally setup and calibrated with the trailer **110** attached to the vehicle **100**, at step **1248**, an input is made with the input device, such as selecting the desired hitch angle between the vehicle **100** and trailer **110** by manipulating the steering input apparatus **125**, as previously described. At step **1250**, the sensor system **1200** begins to monitor the trailer **110** with the primary sensor **1202** to determine the first measured hitch angle  $\gamma(m)$  at step **1252**. In conjunction with the operation of the primary sensor, at step **1254**, the secondary sensor similarly monitors the trailer **110** to determine the indicator **1206** of the actual hitch angle  $\gamma(a)$  at step **1256**. At step **1258**, the first measured hitch angle  $\gamma(m)$  is compared with the indicator **1206** to determine if the measured hitch angle  $\gamma(m)$  of the primary sensor **1202** correlates therewith, and if so, thereby reflecting a generally accurate measurement of the actual hitch angle  $\gamma(a)$ . If the measured hitch angle  $\gamma(m)$  is determined to not correlate with the indicator **1206**, the user may be prompted at step **1260**, such as being alerted with any of the interior or exterior alerts **1240**, **24**, being alerted and/or requested with the vehicle HMI to direct whether the trailer backup assist system **105** should proceed to operate the vehicle **100**, and similarly being alerted and/or prompted with a mobile device via wireless communication **22**, as described above. If the measured hitch angle  $\gamma(m)$  of the primary sensor **1202** correlates with the indicator **1206** of the actual hitch angle  $\gamma(a)$ , then, at step **1262**, the trailer backup assist system **105** may operate to achieve the desired input made with the input device, such as steering the vehicle **100** with the power-steering assist system **115** to achieve the desired hitch angle input with the steering input apparatus **125**.

While the illustrated embodiment of the sensor system **1200** includes a primary sensor **1202** and a secondary sensor **1204**, it should be appreciated that the sensor system **1200** may include addition sensors (tertiary sensor, quaternary sensor, etc.) with additional corresponding indicators for confirming the accuracy of the indicator **1206** from the secondary sensor **1204** and the measured angle  $\gamma(m)$  from the primary sensor **1202**. It is also be understood that the sensor system **1200** may additionally, or alternatively, be adapted for use with other vehicle related applications, such as trailer sway limiters or other conceivable applications relying upon the accuracy of the measured hitch angle  $\gamma(m)$ .

#### Hitch Angle Estimation and Verification

According to an additional embodiment for estimating the actual hitch angle, a system uses an estimated distance between a wireless receiver on the vehicle and a wireless

transmitter on the trailer. The wireless receiver on the vehicle is located at a predetermined distance from a trailer mount and the wireless transmitter on the trailer is located at an end of the trailer opposite the trailer mount. With respect to this embodiment, the system includes a controller for monitoring power returns of a signal transmitted from the transmitter to the receiver and for estimating the distance between the transmitter and the receiver as a function of a path loss propagation of the transmitted signal. The actual hitch angle is then estimated using the estimated distance, the predetermined distance, and a trailer length.

Referring now to FIGS. 32-34, one embodiment the system for estimating the actual hitch angle is shown to include a wireless receiver 1270 on a vehicle 100 with a trailer backup assist system 105. The wireless receiver 1270 is mounted at a known vehicle location, such as a central vehicle body position. In the illustrated embodiment, the vehicle 100 also has a controller 1272 for receiving information from the wireless receiver 1270, which may be a single centralized vehicle controller or a combination of controllers. The controller 1272 may be programmed to perform various functions and control various outputs and may have a memory 1274 associated therewith. The memory 1274 may store various parameters, thresholds, patterns, tables, or maps; for example, parameters may include known, fixed vehicle measurements such as wheel base, vehicle length, trailer length and distances from known parts of the vehicle. The controller 1272 receives information from a number of sensors on or around the vehicle 100 associated with one or more sensing systems 1276, which may include, but are not limited to, speed sensors, yaw rate sensor, lateral acceleration sensor, roll rate sensor, vertical acceleration sensor, a longitudinal acceleration sensor, a pitch rate sensor, and a steering angle position sensor. These sensors may also be part of an inertial measurement unit that would most likely be located at the center of the vehicle body.

As shown in FIGS. 32-33, a trailer 110 may be towed behind the vehicle 100. The trailer 110 may include a tongue 112 and trailer wheels, as well as a trailer brake and electrical components such as lights. A wiring harness 1278 may be used to couple the trailer 110 to the electrical system of the vehicle 100 and ultimately to the controller 1272. The trailer 110 is coupled to the vehicle 100, as by a hitch ball 15 or other mount on the vehicle 100, through a coupler assembly 114 located at the end of the trailer tongue 112. A distance  $d_r$  defines a reference distance which is the distance between the wireless receiver 1270 on the vehicle 100 and the hitch ball 15 or other mount on the vehicle 100. This is a fixed distance and may be stored in memory 1274. The coupler assembly 114 may have a hitch angle sensor 1226 associated therewith. Alternatively, the hitch angle sensor 1226 may be associated with the mount on the vehicle 100. The hitch angle sensor 1226 is used to determine the angle position of the trailer 110 relative to the vehicle 100. Various types of hitch angle sensors, such as resistive, inductive, ultrasonic, or capacitive type sensors may be used, in addition to other hitch angle sensor system disclosed herein.

A wireless transmitter 1280 is positioned on the trailer 110 at a known location, preferably at the end of the trailer. This wireless transmitter 1280 is in communication with the wireless receiver 1270 that is located on the vehicle 100. The wireless receiver 1270 has been placed at a known location of the vehicle 100 such that a reference distance,  $d_r$ , from the receiver 1270 to the hitch ball 15 at the rear of the vehicle 100 is known and stored in memory 1274. Examples of wireless transmitting and receiving devices that may be used are Radio Frequency Identification (RFID), Bluetooth, and the like. As

discussed above, the wireless receiver 1270 is positioned at a location on the vehicle 100 the predetermined distance,  $d_r$ , from the vehicle's trailer mount or hitch ball 15. The wireless transmitter 1280 and the wireless receiver 1270 are compatible units that transmit and receive signals between the vehicle 100 and the trailer 110. The controller 1272 monitors the power returns of the transmitted signals. By monitoring the power returns of signals sent by the transmitter to the receiver, the controller 1272 may estimate a distance,  $d$ , between the vehicle 100 and the trailer 110.

The disclosed subject matter also uses a trailer length,  $l_T$ . This value may be a known value entered by the driver, stored in controller memory, or otherwise sensed, calculated or estimated. For example, an accurate estimate of trailer length,  $l_T$ , is possible using measurements of the signal transmitted from the wireless transmitter 1280 on the trailer 110 to the wireless receiver 1270 on the vehicle 100 when the hitch angle is zero. It is also possible to estimate the trailer length when the measurements are taken while the vehicle yaw rate is zero for a predetermined period of time.

The hitch angle is thereby estimated using the trailer length,  $l_T$ , and path loss propagation of a signal transmitted from the transmitter on the trailer 110 to the receiver 1270 on the vehicle 100. The hitch angle estimate may then be used as an input for control algorithms associated with a variety of vehicle systems 1281 such as trailer sway, trailer backup assist, stability control and other systems. Alternatively, the hitch angle estimate may be used to verify, or validate, the measurement taken by a hitch angle sensor.

Referring to FIG. 33, a block diagram of a vehicle 100 and trailer 110 combination, where a hitch angle is non-zero, is shown with respect to the law of cosines:

$$A^2 = B^2 + C^2 - 2BC \cos(a)$$

The vehicle 100 has the trailer 110 attached thereto with the receiver 1270 located on the vehicle a predetermined reference distance,  $d_r$ , from the trailer hitch ball 15, which corresponds to B for the triangle reflecting the law of cosines in FIG. 33. The trailer length,  $l_T$ , is shown and the transmitter 1280 is located at the end of the trailer 110. The trailer length,  $l_T$ , corresponds to C in the law of cosines. The distance,  $d$ , between the transmitter 1280 and the receiver 1270 is shown, which corresponds to A in the law of cosines. The reference distance,  $d_r$ , is a known distance that may be stored in memory 1274. The trailer length,  $l_T$ , may also be a known distance that is stored in memory 1274 or it may be estimated or calculated as described later herein. The distance,  $d$ , is calculated as described hereinafter with reference to FIG. 34.

Referring to FIG. 34, a flow chart of the method 1282 for estimating a hitch angle in accordance with the disclosed subject matter is shown. The method 1282 can be carried out using the vehicle and trailer architecture discussed above in reference to the vehicle 100 and trailer 110 for FIG. 32. Accordingly the hitch angle estimate may be supplied to any vehicle system 1281 requesting the information.

An operation 1284 is performed for requesting hitch angle estimation. A request for hitch angle estimation may come from a vehicle control system 1281 that requires the information as an input to the control algorithm associated therewith or it may come from a control system 1281 that wants to validate or verify a hitch angle provided by a hitch angle sensor. Examples of vehicle control systems 1281 that may request hitch angle information may be a trailer backup assist system 105, a trailer sway control system, a trailer brake control system, and a vehicle dynamic control system such as roll stability control or yaw stability control. These are only a

few examples of systems **1281** that may utilize hitch angle information as an input to a control algorithm.

An operation **1286** is performed to monitor power returns of signals transmitted from the trailer **110** to the vehicle **100**. Path loss is proportional to the square of the distance between the transmitter and the receiver and power returns of signals transmitted may be used to estimate a distance between the transmitter and the receiver. The power returns are measured, at the receiver, at predetermined time intervals and stored in controller memory over a predetermined period of time. The power returns may be accessed by the controller for various operations and/or functions that use the values to estimate hitch angle.

An operation **1288** is performed to estimate the distance,  $d$ , between the transmitter and the receiver. Estimating the distance,  $d$ , between the wireless transmitter and the wireless receiver **1270** is accomplished by using the, measured power returns or measured path loss of the signal being transmitted. Path loss is proportional to the square of the distance between the transmitter and the receiver, and also to the square of the frequency of the transmitted signal. Signal propagation may be represented by Friis transmission formula:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L}$$

where,

$P_t$  is the transmission power in Watts,

$G_t$  and  $G_r$  are gains associated with the receiver and the transmitter respectively,

$\lambda$  is the wavelength,

$L$  are system losses, and

$d$  is the distance between the transmitter and the receiver.

Accordingly, transmission power decreases at a rate proportional to  $d^2$ . Therefore, knowing the path loss,  $PL$ , associated with the transmitted signal will provide an estimate of the distance,  $d$ , between the transmitter and the receiver. Path loss ( $PL$ ) is represented by the following equations:

$$PL_{dB} = 10 \log \frac{P_t}{P_r} = -10 \log \left( \frac{G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \right)$$

$$PL_{dB} = -10 \log \left( \frac{G_t G_r \lambda^2}{(4\pi)^2 L} \right) + 10 \log(d^2)$$

$$PL_{dB} = -10 \log \left( \frac{G_t G_r \lambda^2}{(4\pi)^2 L} \right) + 20 \log(d)$$

$P_r$  decreases at a rate that is proportional to  $d^2$ . The power of the signal received at the receiver may be represented as:

$$P_r(d) = P_r(d_0) \left( \frac{d_0}{d} \right)^2 \text{ for } d > d_0 > d_f$$

The distance,  $d$ , may be derived from this formula and represents the overall distance between the transmitter on the trailer and the receiver on the vehicle. The distance,  $d_0$ , is a known received power reference point and the distance,  $d_f$  is a far-field distance.

The reference distance,  $d_r$ , is known. If the trailer length,  $l_T$  is known, then an operation **1289**, using the distance,  $d$ , the trailer length,  $l_T$ , the known reference distance,  $d_r$ , between the receiver and the trailer hitch, and the law of cosines, is

performed to calculate the hitch angle. From the law of cosines, provided above, the hitch angle is given by:

$$a = \cos^{-1} \left[ \frac{A^2 - B^2 - C^2}{-2BC} \right]$$

An operation **1290** is performed in which the vehicle system that is requesting the information receives the hitch angle estimation. The disclosed subject matter provides an estimate of hitch angle even when a hitch angle sensor is unavailable. If a system relies on a hitch angle sensor, the disclosed subject matter may provide verification, as a redundant sensor, that the hitch angle sensor is operating properly.

As discussed above, the trailer length,  $l_T$ , may be a known value stored in memory or it may be a value that is calculated according to the disclosed subject matter. The trailer length may be calculated **1292** by comparing distances,  $d$ , between the transmitter and the receiver that have been estimated and stored in memory over a period of time. A predetermined number of distance estimates may be stored in controller memory. A comparison of the stored distances may result in a largest distance may be identified. The largest distance estimate may be associated with a zero hitch angle. This identified largest distance, less the known reference distance,  $d_r$ , will be representative of, and may be stored as, the trailer length,  $l_T$ .

As an alternative, the trailer length,  $l_T$ , may be estimated using a yaw rate provided by a yaw rate sensor on the vehicle to determine when the trailer is a zero hitch angle. A yaw rate sensor is typically available as part of the sensor system **1200** on the vehicle. A zero yaw rate is an indicator that a vehicle is travelling along a straight path, i.e., the vehicle is not turning. The fact that the yaw rate is zero alone is not adequate to identify a zero hitch angle because the vehicle may have just stopped turning even though a non-zero hitch angle exists. However, monitoring yaw rate over time will provide confirmation that the vehicle has driven straight forward for a sufficient predetermined period of time while maintaining a zero or near zero yaw rate. A zero yaw rate, sensed over time, provides an indication that the trailer has straightened out and it can be inferred that the hitch angle is zero at that point. Upon verification of zero hitch angle, the operation to calculate trailer length **1292** is performed. The estimated distance between the transmitter and the receiver when the hitch angle is zero less the predetermined distance,  $d_r$ , defines the trailer length,  $l_T$ .

The predetermined period of time that the yaw rate should remain at zero before the assumption that the hitch angle is zero will be associated with an actual distance the vehicle trailer combination needs to travel to ensure that the hitch angle is zero. This may be determined through testing and stored in the controller memory.

The disclosed subject matter is advantageous in that it provides an estimate of hitch angle whether or not a hitch angle sensor is present on a vehicle. The disclosed subject matter is even advantageous for a vehicle that has a hitch angle sensor in that it provides a method for verifying, or validating, the accuracy of a hitch angle sensed by a hitch angle sensor. This is especially important for vehicle systems that rely critically on the value of the hitch angle being sensed, for example, trailer backup assist systems, trailer sway control systems and trailer brake control systems.

Hitch Angle Calibration

As previously mentioned with reference to FIG. 10 and a driver's interaction with the human machine interface (HMI)

device 102, after the trailer setup module 600 is complete at step 620, the calibration module 700, according to one embodiment, calibrates the curvature control algorithm with the proper trailer measurements and calibrates the trailer backup assist system for any hitch angle offset that may be present. In the one embodiment, the calibration module 700 may instruct the driver to pull the vehicle-trailer combination straightforward until a hitch angle sensor calibration is complete, which may be notified to the driver via the HMI device 102. Depending on any error resulting from the trailer measurements or the potential inability of the vehicle to be pulled straight forward, additional and alternative embodiments of calibrating the trailer backup assist system are described herein.

With reference to FIG. 35, the vehicle trailer backup assist system 105 is illustrated having the trailer backup assist control module 120 in communication with the sensor system 1200 and the trailer backup steering input apparatus 125 as part of the trailer backup assist system 105. The trailer backup assist system 105 in the illustrated embodiment, receives sensor information from the one or more hitch angle sensors 1312, a vehicle yaw rate sensor 1314, and a vehicle speed sensor 1316, and may communicate with other conceivable sensors on the vehicle 100 or trailer 110. For instance, the illustrated embodiment of the trailer backup assist system 105 also communicates with the vehicle transmission controller 1318, such as receiving the presently engaged transmission gear. Furthermore, the trailer backup assist control module 120 is also in direct communication with the power steering assist system 115, which has the power steering assist control module 135 for communicating with the steering angle detection apparatus 140 and a servo steering motor 1300, or servomotor, for operating the steered wheels 1302 of the towing vehicle 100 (FIG. 36). The illustrated embodiment of the trailer backup assist control module 120 includes a microprocessor 1304 for processing one or more routines stored in the corresponding memory 1306 of the trailer backup assist control module 120. The memory in one embodiment includes a hitch angle calibration routine 1308 and an initiating routine 1310. It should be appreciated that the trailer backup assist control module 120 may be a standalone dedicated controller or may be a shared controller integrated with other control functions, such as integrated with the sensor system 1200, the trailer backup steering input apparatus 125, or other systems of the towing vehicle.

As shown in FIG. 36, a schematic illustration of the vehicle 100 and trailer 110 combination are overlaid with an x-y coordinate system showing kinematic variables and angles, including the steering angle  $\delta$ , trailer length D, and hitch angle  $\gamma$ , which may be affected by the dynamics of the vehicle 100 and trailer 110 combination and representable in kinematic equations, as similarly discussed with reference to FIG. 5.

Referring to FIGS. 37-38, a method is shown for estimating the actual hitch angle  $\gamma(a)$  between the vehicle 100 and the trailer 110, according to one embodiment. The method provides for sensing a measured hitch angle  $\gamma(m)$  with at least one hitch angle sensor 1312 (FIG. 35) on the vehicle 100 and sensing a steering angle  $\delta$  of the steered wheels 1302 (FIG. 36) of the vehicle 100. Further, the method provides for reversing the vehicle 100, and thereby determining an offset  $\gamma(o)$  between the measured hitch angle  $\gamma(m)$  and the actual hitch angle  $\gamma(a)$  when the measured hitch angle  $\gamma(m)$  and the steering angle  $\delta$  are substantially constant while the vehicle 100 is reversing.

As reflected in the diagram shown in FIG. 36, when the hitch angle  $\gamma$  and steering angle  $\delta$  are substantially constant,

the yaw rate of the vehicle 100 is also substantially constant and equal to the yaw rate of the trailer 110. This interaction is used to formulate kinematic equations that can be solved for determining the offset  $\gamma(o)$  between the measured hitch angle  $\gamma(m)$  and the actual hitch angle  $\gamma(a)$ . Specifically, the yaw rate of the vehicle 100, as measured by the vehicle yaw rate sensor 1314 (FIG. 35) or another conceivable onboard vehicle sensor that may be configured to sense the yaw rate, provides the following equation:

$$\frac{d\alpha}{dt} = -\frac{v}{W} \tan \delta$$

Furthermore, the yaw rate of the trailer can be represented with the following equation:

$$\frac{d\beta}{dt} = \frac{v}{D} \sin \gamma + \frac{Lv}{DW} \cos \gamma \tan \delta$$

Where,

$\delta$  is the steering angle of the front wheels

D is the distance from the hitch to the trailer axle

W is the vehicle wheelbase (distance between both axles)

L is the distance from the vehicle rear axle and hitch

$\gamma$  is the hitch angle

Accordingly, when the yaw rate of the vehicle 100 and the trailer 110 become equal, the actual hitch angle  $\gamma(a)$  will likely be constant, such that the desired hitch angle provided by the trail backup steering input apparatus 125, such as the previously described rotatable input control device shown in FIG. 2, is also constant and substantially achieved. For example, the desired hitch angle received from the trailer backup steering input apparatus 125 may be constant when the driver attempts to reverse the trailer 110 in a straight line with the vehicle 100 (i.e. a zero curvature command) or when the driver inputs a maximum knob angle command. The resulting constant hitch angle results in the following equation:

$$c = a \cos \gamma + b \sin \gamma$$

This equation can be rewritten as follows:

$$c = a \sqrt{1 - \sin^2 \gamma} + b \sin \gamma$$

The above equation can be solved with the quadratic equation that solves for the hitch angle  $\gamma$ . Thereafter, when breaking up the hitch angle  $\gamma$  into a measured hitch angle  $\gamma(m)$  and an offset angle  $\gamma(o)$ , the equation can be rewritten as follows:

$$\gamma_o = \arcsin \frac{bc \pm a \sqrt{b^2 + a^2 - c^2}}{b^2 + a^2} - \gamma_m$$

Where,

$$c = -\frac{1}{W} \tan \delta$$

$$b = \frac{1}{D}$$

$$a = \frac{L}{DW} \tan \delta$$

Accordingly, the hitch angle offset  $\gamma(o)$  may be determined as a function of the length D of the trailer 110, the wheelbase length W of the vehicle 100, and the distance L from a rear axle of the vehicle 100 to the trailer 110 as shown in FIG. 36,

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while meeting the conditions provided above to use such an equation. Specifically, the conditions generally include that the vehicle **100** and trailer **110** are reversing and that the measured hitch angle  $\gamma(m)$  and the steering angle  $\delta$  are substantially constant during the reversing motion for at least a threshold period of time or over a threshold distance of motion.

As illustrated in FIG. 37, the calibration module **700** processes one embodiment of the hitch angle calibration routine **1308** to provide the method according to the following steps. At step **1320**, the system receives generally fixed characteristics of the vehicle **100** and the trailer **110**, including the trailer length  $D$ , the vehicle wheelbase length  $W$ , and the distance  $L$  from the vehicle's rear axle to the hitch connection. These generally fixed characteristics are described as such because the vehicle **100** and trailer **110** dimensions can be preloaded or looked up in product specifications, and if these dimensions are not known or otherwise already determined by the system, they can be measured and input into the memory **1306** or other vehicle memory prior to operating the vehicle **100** with the trailer backup assist system **105**. The hitch angle calibration routine **1308** shown in FIG. 37, also provides at step **1322**, confirming that the vehicle **100** is reversing when the sensors of the sensor system **1200** are taking continuous measurements of the vehicle **100** and trailer **110** variables. Specifically, the system may confirm that the vehicle **100** is reversing with use of directional speed sensors, the gear position of the transmission controller **1318**, GPS inputs, or other conceivable indicators of vehicle **100** direction.

At step **1324**, the system conducts the initiating routine **1310** to further confirm that the vehicle **100** and trailer **110** combination are in a condition to determine the offset  $\gamma(o)$  between the measured hitch angle  $\gamma(m)$  and the actual hitch angle  $\gamma(a)$ . As shown in FIG. 38, one embodiment of the initiating routine **1310** includes determining a compensated steering wheel angle **1326**, calculating a filtered steering wheel angle rate **1328**, and then determining at step **1330** whether the filtered steering wheel angle rate is less than a maximum allowable steering angle rate for the offset calculation. Also, the initiating routine **1310** takes the measured trailer angle  $\gamma(m)$  at step **1332** and calculates a filtered trailer angle rate over time at step **1334**. The initiating routine then at step **1336** determines whether the filtered trailer angle rate is less than a maximum allowable trailer angle rate for determining the offset calculation. Further, the initiating routine **1310** takes the sensed or otherwise calculated vehicle speed from step **1338** and further calculates a filtered vehicle speed at step **1340**. The filtered vehicle speed is then processed at step **1342** to determine whether it is less than a maximum allowable vehicle speed for determining the offset calculation. If the conditions of the initiating routine **1310** are met at step **1344**, the trailer backup assist system **105** allows the hitch angle calibration routine **1308** to continue towards determining the offset  $\gamma(o)$ .

With further reference to FIG. 37, when the initiating routine **1310** is complete, the hitch angle calibration routine at step **1346** determines whether the hitch angle rate and the steering angle rate are both substantially zero, or alternatively stated, whether the hitch angle and the steering angles are substantially constant. If the hitch angle rate and the steering angle rate are both not substantially zero, the hitch angle calibration routine **1308** continues to conduct the initiating routine **1310** at step **1324** and continues to take measurements with the sensor system **1200** until the hitch angle rate and steering angle rate are substantially zero. Once they are both substantially zero, the hitch angle calibration routine **1308**

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then determines the actual hitch angle at step **1348** based on the vehicle **100** and trailer **110** generally fixed characteristics, as identified in the equations above. With the actual hitch angle  $\gamma(a)$ , the hitch angle calibration routine **1308** may then determine the offset  $\gamma(o)$  between the actual hitch angle  $\gamma(a)$  and the measured hitch angle  $\gamma(m)$  at step **1350**. Upon determination of the offset  $\gamma(o)$ , the calibration module is complete and the trailer backup assist system **105** may proceed for operation.

In an additional embodiment of the hitch angle calibration routine **1308**, as illustrated in FIG. 39, a method is provided for calibrating the trailer backup assist system **105** for the trailer **110** attached to the vehicle **100**, which provides driving the vehicle **100** forward substantially straight above a threshold speed. The method also provides sensing a yaw rate of the vehicle **100** and sensing a measured hitch angle  $\gamma(m)$  of the trailer **110**. Further, the method provides for determining an angle rate based on the measured hitch angle  $\gamma(m)$ , and then determining an offset  $\gamma(o)$  between the measured hitch angle  $\gamma(m)$  and the actual hitch angle  $\gamma(a)$  when the yaw rate and the angle rate are substantially zero.

In the previously described embodiment of the hitch angle calibration routine **1308** with reference to FIG. 37, the vehicle **100** is reversing and therefore such an embodiment is configured for situations when the vehicle **100** may not be able to drive forward far enough to calibrate the trailer backup assist system **105**. However, when space is available to drive the vehicle **100** forward, an alternative method may be used to determine the offset  $\gamma(o)$  between the actual hitch angle  $\gamma(a)$  and the measured hitch angle  $\gamma(m)$  that does not rely upon the accuracy of the measured or otherwise determined trailer geometry and dimensions. Specifically, when setting up the trailer **110** with the vehicle **100**, in one embodiment, the user may be instructed to measure various dimensions of the trailer **110**, including the trailer length  $D$ . The dimensions of the vehicle **100**, however, may be measured with a high degree of accuracy upon assembly of the vehicle or otherwise supplied in an accurate manner to the trailer backup assist system **105**, such as with a hookup table provided by the vehicle manufacture.

With reference to FIG. 39, at step **700** the trailer backup assist system **105** again begins to calibrate the system for the trailer **110** attached to the vehicle **100**. At step **1352**, the system receives the vehicle characteristic including the dimensions of the vehicle **100** and the operating characteristics, such as the present gear of the transmission. Then at step **1354**, the system confirms that the vehicle is driving forward while the sensors of the sensor system **1200** take measurements and other readings. Notably, in this illustrated embodiment, the sensors utilized include a sensor for determining the vehicle yaw rate, such as an onboard yaw rate sensor **1314** or a separate sensor configured to determine the yaw rate of the vehicle. Also, the sensors being utilized by this embodiment of the hitch angle calibration routine include at least one hitch angle sensor **1312**, as previously described with reference to the sensor system **1200**.

Still referring to FIG. 39, at step **1356**, the steered wheels **1302** of the vehicle **100** are steered straight while the vehicle **100** is traveling forward. It is contemplated that in one embodiment the user may be instructed to steer the vehicle straight by manually controlling the steering wheel. In an additional embodiment, the vehicle **100** may automatically steer the vehicle **100** straight using the powering steering assist system **115**. More specifically, the trailer backup assist system **105** may operate the steered wheels **1302** of the vehicle **100** using the servo steering motor **1300** in conjunction with the steering angle detection apparatus **140**.

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Once the sensor readings are being received and the vehicle is being steered straight and driving forward, the illustrated embodiment of the hitch angle calibration routine **1308** then proceeds to process an initiating routine **1310** at step **1358**. The initiating routine **1310** of the present embodiment may, similar to the initiating routine illustrated in FIG. **38**, calculate filtered values for the steering wheel angle rate, the hitch angle rate, and the vehicle speed. Furthermore, these filtered values may be compared against threshold values to ensure the hitch angle calibration routine is performed when vehicle conditions are acceptable for such calculation. Specifically, the filtered steering angle rate may be less than a maximum allowable steering angle rate, the trailer angle rate may be less than the maximum allowable trailer angle rate, and the filtered vehicle speed may be less than the maximum allowable vehicle speed, such as 10 mph, 15 mph, or other conceivable threshold speed. When these or more or fewer conditions are met, the system may proceed to the following step of the hitch angle calibration routine.

As also illustrated in FIG. **39**, at step **1360** the hitch angle calibration routine **1308** determines whether the hitch angle rate and the yaw rate are both substantially zero. Specifically, the determination of reaching a value of substantially zero may be one or a combination of the value being within a close proximity to zero or the value being zero or substantially zero over a predetermined period of time. It is contemplated that the increment of time may be proportional to the filtered vehicle speed, such that increasing speed of the vehicle results in decreasing the increment of time the measured hitch angle  $\gamma(m)$  and the steering angle must be substantially constant to determine the offset  $\gamma(o)$ . It is also contemplated that the offset may be determined when the measured hitch angle and the steering angle are substantially constant while the vehicle and the trailer are reversing over a threshold distance, such as a distance is greater than half a circumference of a steered wheel of the vehicle or other conceivable distances. When the system makes a determination that both values are substantially zero, the system, at step **1362** is then able to determine the actual hitch angle  $\gamma(a)$  based upon the vehicle characteristics. In one embodiment, when the above conditions are met the actual hitch angle  $\gamma(a)$  will be zero. However, some vehicle characteristics, such as an offset hitch location, may result in the actual hitch angle  $\gamma(a)$  deviating from zero with these conditions met. At step **1364** the system then determines the offset  $\gamma(o)$  between the actual hitch angle  $\gamma(a)$  and the measured hitch angle  $\gamma(m)$  for purposes of operating the trailer backup assist system **105**. Again, at step **704** the trailer backup assist system **105** may notify the driver that the calibration is complete and may store the hitch angle offset value in memory to be associated with the attached trailer **110**.

Referring now to FIG. **40**, an additional embodiment of the hitch angle calibration routine **1308** is illustrated that may consider the vehicle's direction of movement or potential direction of movement before choosing a method for determining the offset  $\gamma(o)$  of the measured hitch angle  $\gamma(m)$ . The vehicle's direction of movement may be based upon the presently engaged gear of the transmission, such as drive or reverse for automatic transmissions. The vehicle's potential direction of movement, however, may be based upon the available space in front of or behind the vehicle and trailer combination. At step **1366**, if the vehicle **100** is moving in either the forward or rearward directions, the system may determine if enough available space exists for the vehicle **100** to continue moving in such direction and complete the calibration of the trailer backup assist system **105**. If enough available space is not present, the hitch angle calibration

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routine **1308** of the illustrated embodiment may instruct the driver to move the vehicle **100** in the opposite or an alternative direction, provided enough available space exists in such direction to complete the calibration. Also, if the vehicle **100** is not moving, the system may determine the preferred direction of movement for the vehicle **100** and trailer **110** to move to have enough space for the vehicle **100** to complete the calibration of the trailer backup assist system **105**. At step **1368** the system may instruct the driver, such as through the HMI, to drive either forward or in reverse, as determined in the previous step **1366**. Based on which direction the vehicle is instructed to move, this embodiment of the hitch angle calibration routine **1308** may employ one of two alternative methods to determine the actual hitch angle  $\gamma(a)$  for completing the calibration. Specifically, if the vehicle **100** is traveling forward, at step **1370**, the system then proceeds to ensure that the vehicle is steered straight **1372**, while sensing the yaw rate of the vehicle **1374** and sensing the hitch angle rate **1376**. The sensed hitch angle  $\gamma(m)$  is used by the system to determine the hitch angle rate at step **1378** and then continue on to step **1380** to determine when the hitch angle rate and the yaw rate of the vehicle are substantially zero, similar to the method previously described with reference to the embodiment disclosed in FIG. **39**. When the hitch angle rate and the yaw rate of the vehicle are substantially zero, at step **1380** the hitch angle calibration **1308** routine may determine the actual hitch angle  $\gamma(a)$  to be substantially zero, which may then be used in conjunction with the measured hitch angle  $\gamma(m)$  to determine the offset  $\gamma(o)$  at step **1382**.

Alternatively, if the vehicle **100** is reversing or instructed to reverse, at step **1384**, once the vehicle **100** is reversing, the system proceeds to sense the steering angle  $\delta$  of the vehicle **100** at step **1386** and sense the hitch angle  $\gamma(m)$  at step **1388** to then determine the hitch angle rate and the steering angle rate at step **1390**. At step **1392** the system determines when both the hitch angle rate and the steering angle rate are substantially zero. When both these values are substantially zero, the hitch angle calibration routine **1308** may determine the offset  $\gamma(o)$  of the measured hitch angle  $\gamma(m)$  based upon the length  $D$  of the trailer **110**, the wheelbase length  $W$  of the vehicle **100**, and the distance  $L$  from the rear axle of the vehicle **100** to the trailer **110**, as generally set forth in the embodiment of the hitch angle calibration routine **1308** described with reference to FIGS. **37** and **38**. In the embodiment disclosed in FIG. **40**, once the hitch angle offset  $\gamma(o)$  is determined at step **1382**, the calibration routine commences at step **704** and may notify the driver, such as via the HMI or another similar notification.

#### Hitch Angle Sensor Assembly

As disclosed herein, it is advantageous to use information that is representative of a hitch angle between a vehicle and a trailer attached to the vehicle, also described herein as the actual hitch angle  $\gamma(a)$  or trailer angle. For instance, the trailer backup assist system **105** and other conceivable vehicle systems may utilize hitch angle information as an input into the system. In accordance with the previous disclosure, the estimated hitch angle  $\gamma$  may be derived from information collected from one or more sensors on the vehicle, one or more sensors on the trailer, a hitch angle detection apparatus **130** on the vehicle **100**, a hitch angle detection component **155** on the trailer **110**, or other conceivable sensor systems.

Referring now to FIGS. **41-47**, one embodiment of a hitch angle sensor assembly **1400** is illustrated for determining a hitch angle  $\gamma$  between a trailer **110** attached to a vehicle **100**. The hitch angle sensor assembly **1400** includes a housing **1402** fixed to a hitch ball **15** on the vehicle **100**, whereby an element **1404** attached to the trailer **110** rotates relative to the

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housing 1402 about an axis 1406 defined by the hitch ball 15. The hitch angle sensor assembly 1400 according to another embodiment defines the housing 1402 as a spacer 1408 fixed between a hitch ball 15 and a mounting surface 1410 on the vehicle 100. An element 1404 may be rotatably coupled with the spacer 1408 for rotating about the axis 1406 defined by the hitch ball 15. A connecting member 1412 may secure the element 1404 to the trailer 110 for rotating the element 1404 in conjunction with angular movement of the trailer 110. A proximity sensor 1414 is coupled with the spacer 1408 and senses movement of the element 1404 for determining the hitch angle. It is contemplated that the element 1404 in other embodiments may be alternatively secured to the trailer 110 to rotate the element 1404 relative to the sensor upon angular movement of the trailer 110. These and other embodiments of the hitch angle sensor assembly 1400 are described in more detail below.

As shown in the embodiment illustrated in FIGS. 41-42, the vehicle 100 includes a vehicle hitch connector 1416 that has a hitch ball 15 coupled with a mounting surface 1410 on the vehicle 100, which is generally centered across a width of the vehicle 100 at a rear portion 1426 of the vehicle 100 proximate the bumper beam 1418. The trailer 110, according to the illustrated embodiment, includes a tongue 112, shown as a longitudinally extending bar, with a coupler assembly 114 arranged at a forward end thereof. The coupler assembly 114 attaches to the hitch ball 15 to provide a pivoting connection 117 between the vehicle 100 and the trailer 110. However, it is conceivable that the trailer 110 may include an alternative coupler assembly 114 and the vehicle 100 may include an alternative hitch connector, such as a fifth wheel connection, a European-style hitch ball, or other conceivable configurations to provide a pivoting connection 117 between the vehicle 100 and the trailer 110.

As also shown in FIG. 42, the vehicle 100 includes a receiver 1420 having a longitudinally oriented aperture that engages a hitch mount 1422. As such, the hitch mount 1422 includes an attachment member 1424 having a generally square cross section to engage the aperture of the receiver 1420. A rear portion 1426 of the hitch mount 1422 is integrally coupled with the attachment member 1424 and includes a substantially planar mounting surface 1410 with a generally horizontal orientation. In additional embodiments, the hitch receiver 1420 may be configured with a mounting surface 1410 arranged at a higher or lower elevation, commonly referred to as a hitch drop, that is configured for a specific trailer 110. The mounting surface 1410 of the hitch mount 1422 may also have an alternative shape or curvature from that illustrated. Furthermore, it is contemplated that the mounting surface 1410 may include a lower surface 1428 (FIG. 42A) of the hitch mount 1422, a substantially horizontal location directly on the bumper beam 1418, or other suitable towing locations on the vehicle 100. The hitch ball 15 in the illustrated embodiment is coupled with the mounting surface 1410 of the hitch mount 1422 proximate a rearward end of the hitch mount 1422.

With further reference to the embodiment illustrated in FIG. 42-42A, the connecting member 1412 couples with a bottom surface 1430 of the tongue 112 of the trailer 110 at a distance longitudinally spaced from the hitch ball 15. In the illustrated embodiment, the connecting member 1412 comprises a cord 1432 having end portions 1434 coupled with the element 1404 of the hitch angle sensor on opposing sides of the hitch ball 15. The cord 1432 extends rearward from the end portions 1434 to couple with the trailer 110 at a central portion 1436 of the cord 1432. Specifically, in the illustrated embodiment, the cord 1432 has a loop 1438 formed at the

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central portion 1436 that substantially encompasses a circumference of a cylindrical magnet 1440 that is configured to magnetically attach to a ferromagnetic portion of the tongue 112 of the trailer 110. The loop 1438 of the cord is secured around the cylindrical magnet 1440 with a cinch 1442 formed between opposing portions of the cord on opposite sides of the cylindrical magnet 1440. The cord 1432 may comprise elastomeric material to allow the cylindrical magnet 1440 to attach to various types of trailers and locations thereon. It is contemplated that the connecting member 1412 may additionally or alternatively include generally inflexible or substantially rigid members that span between the element 1404 of the hitch angle sensor assembly 1400 and the trailer 110.

Referring now to the embodiment illustrated in FIG. 43, the spacer 1408 is shown fixedly coupled between a bottom surface 1444 of the hitch ball 15 and the mounting surface 1410. More specifically, the illustrated embodiment of the hitch ball 15 includes a head portion 1446 having a spherical shape that is connected to a shoulder portion 1448 with a generally disc shape by a neck portion 1450 therebetween. The neck portion 1450 has a substantially cylindrical shape with a central axis 1452 that defines the vertically oriented axis 1406 of the hitch ball 15. As such, the neck portion 1450 is co-axial with the shoulder portion 1448 and the head portion 1446 has a central point substantially in line with the vertical axis 1406. The bottom surface 1444 of the hitch ball 15 is defined by the downward facing surface of the shoulder portion 1448 that is configured to abut the mounting surface 1410 of the hitch mount 1422. In the illustrated embodiment of the hitch angle sensor assembly 1400, the spacer 1408 is fixed between the bottom surface 1444 and the mounting surface 1410, such that the head portion 1446 and the neck portion 1450 of the hitch ball 15 are not interfered with by the hitch angle sensor assembly 1400 during operation of the vehicle 100 and trailer 110.

As illustrated in FIG. 44, the hitch ball 15 is shown having a threaded attachment section 1454 with a cylindrical shape extending downward from the bottom surface 1444 in co-axial alignment with the neck portion 1450 of the hitch ball 15. The diameter of the threaded member is sized to extend through a similarly sized attachment aperture 1456 in the hitch mount 1422, as generally understood in the art. The attachment aperture 1456 in the hitch mount 1422, as illustrated, is substantially cylindrical and vertically oriented to extend between the mounting surface 1410 and the lower surface 1428 of the hitch mount 1422. In the illustrated embodiment, a nut 1458 is provided to threadably engage the threaded member and thereby secure the nut 1458 in abutting contact with the lower surface 1428 of the hitch mount 1422 to provide a compressive force between the bottom surface 1444 of the hitch ball 15 and the mounting surface 1410 for effectuating a secure and generally fixed connection of the spacer 1408 between the hitch ball 15 and the hitch mount 1422.

With further reference to FIG. 44, the spacer 1408 includes a curved channel 1460 about the axis 1406 of the hitch ball 15 in a substantially horizontal plane that is in parallel alignment with the mounting surface 1410. In the illustrated embodiment, the curved channel 1460 is formed around an upper section 1462 of the spacer 1408 to provide a lower section 1464 of the spacer 1408 with sufficient height to accommodate the proximity sensor 1414 coupled therewith. Also, in the illustrated embodiment, a central aperture 1466 is formed vertically through the upper and lower sections for aligning with the attachment aperture 1456 in the hitch mount 1422. A vertical support section 1468 is defined along an internal surface 1470 of the central aperture 1466 between the top

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surface of the spacer 1408 and a bottom surface of the spacer 1408 to withstand loading and compressive forces between the hitch ball 15 and the mounting surfaces 1410. More specifically, the vertical support section 1468 proximate the upper section 1462 includes a wall thickness and a compressive strength sufficient to withstand the forces between the hitch ball 15 and the mounting surface 1410, and thereby prevent deformation or buckling of the spacer 1408. The spacer 1408 may be made from various materials having the qualities described above, and in one embodiment may be formed from a metal or a metal alloy, and in a more preferred embodiment may be a machined steel.

Still referring to FIG. 44, the element 1404 is slidably coupled with the channel on the upper portion of the spacer 1408 to effectuate the ability of the element 1404 to rotate relative to the spacer 1408 about the axis 1406 defined by the hitch ball 15. In the illustrated embodiment, the element 1404 has a ring shape with eyelets 1472 protruding from opposing lateral sides of the element 1404 for engaging end portions 1434 of the connecting member 1412. The element 1404 may also be formed from various materials; however, the element 1404 is preferably formed from a polymer material, and more preferably molded with a plastic material having a low coefficient of friction to slidably rotate about the curved channel 1460 of the spacer 1408.

As shown in the embodiment illustrated in FIG. 45, the element 1404 has a magnetic portion 1472 that is configured for the proximity sensor 1414 to sense a rotated position of the element 1404, which corresponds to a hitch angle of the trailer 110 relative to the vehicle 100. In the illustrated embodiment, the magnetic portion 1472 includes an arcuate shape with a center point 1474 offset from the axis 1406 of the hitch ball 15, such that the arcuate shape varies in radial distance about the axis 1406. Specifically, the arcuate shape of the magnetic portion 1472 has a spacing from the axis 1406 that steadily increases from one end 1475 of the magnet to the other end 1475. Accordingly, it is contemplated that the arcuate shape of the magnetic portion 1472 in other embodiments may not have a circular shape to define a center point, but may still vary in distance about the vertical axis 1406 to provide feedback to the proximity sensor 1414 indicative of the hitch angle. Further, the magnetic portion 1472, in the illustrated embodiment, comprises a strip magnet 1476 having a first side 1478 directed generally away from the vertical axis 1406 and a second side 1480 directed generally toward the axis 1406, such that the first side 1478 has an opposite polarity from the second side 1480. In one embodiment, the first side 1478 of the strip magnet 1476 has a south pole directed away from the vertical axis 1406 and the second side 1480 has a north pole directed toward the vertical axis 1406. It is contemplated that the polarity may be reversed in alternative embodiments, and additionally conceivable that the strip magnet 1476 may have separate magnets arranged in a Halbach array or other arrangements to provide a magnetic field that varies across the proximity sensor 1414 upon rotation of the element 1404 relative to the spacer 1408.

Accordingly, as further illustrated in the embodiment shown in FIG. 45, the proximity sensor 1414 includes a magnetic field sensor 1482, specifically a linear hall effect sensor, that is arranged in a plane generally parallel to the horizontal plane in which the element 1404 rotates about the spacer 1408. However, it is contemplated that the magnetic field sensor 1482 may be alternatively arranged in a different location or a different orientation relative to the spacer 1408 to provide varied and distinguishable voltage outputs upon rotation of the element 1404 relative to the spacer 1408.

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With reference to FIGS. 44-46, the trailer 110 is pivoted away from the substantially in-line position shown in FIG. 45 to a right side orientation shown in FIG. 46 with a first hitch angle 1484 and a left side orientation shown in FIG. 47 with a second hitch angle 1486. As shown in FIG. 46, the connecting member 1412 rotates the element 1404 with the angular change of the trailer 110 relative to the vehicle 100. Upon the rotation to the first hitch angle 1484, the magnetic portion 1472 of the element 1404 moves from intersecting a central location 1488 of the magnetic field sensor 1482 (FIG. 45) to intersecting a forward location 1490 of the magnetic field sensor 1482. The magnetic field sensor 1482 outputs a lower voltage at the forward location 1490 than the central location 1488 such that the difference is measurable and convertible to the first hitch angle 1484 that, in general, accurately correlates with the hitch angle  $\gamma$  between the vehicle 100 and trailer 110.

Alternatively, in FIG. 47 upon rotation to the second hitch angle 1486, the magnetic portion 1472 of the element 1404 is rotated, such that the magnetic portion 1472 intersects the proximity sensor 1414 at a rearward location 1492. The linear hall effect sensor, in the illustrated embodiment, is configured to sense the intersecting location of magnetic portion 1472 within the horizontal plane of the hall effect sensor. Accordingly, the linear hall effect sensor outputs a substantially lower voltage in the right side orientation versus the left side orientation, corresponding with a small output value as shown in FIG. 47 and a greater output value as shown in FIG. 46, whereby the controller of the hitch angle sensor assembly 1400 is configured to correlate an output value larger than the inline orientation shown in FIG. 45 with a right side orientation of the trailer 110 and an output value less than the inline orientation with a left side orientation of the trailer 110. Accordingly, the magnetic field sensor senses the field strength of the magnet that corresponds with the rotated position of the element 1404 relative to the housing 1402, whereby the rotated position is used to determine the hitch angle  $\gamma$  between the trailer 110 and the vehicle 100. It is also understood that the proximity sensor 1414 in additional embodiments of the hitch angle sensor assembly 1400 may include a potentiometer, a capacitive sensor, an inductive sensor, and other conceivable sensors as generally understood by one having ordinary skill in the art.

#### Horizontal Camera to Target Distance Calculation

In order to implement some of the features described herein, a user is typically required to set up the trailer backup assist system 105. This can include properly placing a target on a trailer as well as obtaining one or more measurements associated with a particular vehicle-trailer configuration. Two user-obtained measurements can include a horizontal camera to target distance and a target to ground distance. Since the user is typically charged with performing these measurements, there is a possibility for erroneous measurements being reported to the trailer backup assist system 105, thereby potentially diminishing the accuracy of hitch angle detection and/or other actions performed by the trailer backup assist system 105. To lessen the likelihood of a user reporting erroneous measurements during the set up process, a system and method is disclosed herein that at most, requires the user to measure only the target to ground distance, which is supplied to the trailer backup assist system 105 and used to calculate the horizontal camera to target distance. In this manner, the potential for human error is reduced and as an additional benefit, the process of setting up the trailer backup assist system 105 is shortened.

Referring to FIG. 48, the trailer backup assist system 105 is shown including a camera 2000, an input device 2005, and a



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controller **2010** configured to communicate with the input device **2005** and the camera **2000**. According to one embodiment, the camera **2000** can be an existing rearview camera of a vehicle **2015** and is configured to image a target **2020** that is attached to/integral with a surface of a trailer **2025**. The input device **2005** can be a human machine interface (e.g., HMI **102**) through which a user interacts with the trailer backup assist system **105**. Additionally or alternatively, the input device **2005** can include a portable electronic device (e.g., portable device **26** in FIG. **13**) configured to wirelessly communicate with the trailer backup assist system **105** such as a smartphone, tablet, and the like. As described previously, the user can interact with the input device **2005** via any conventional means, such as, but not limited to, depressing a button, rotating a knob, flipping a switch, and/or using a finger to perform a touching/tracing action on a display screen.

The controller **2010** can be any controller of an electronic control system that provides for setup functionality of the trailer backup assist system **105**. The controller **2010** can include a processor **2030** and/or other analog and/or digital circuitry for processing one or more routines. Additionally, the controller **2010** can include memory **2035** for storing one or more routines. According to one embodiment, the controller **2010** can be configured to receive and process information from the input device **2005** and image data from the camera **2000**.

Discussion now turns to a method for calculating a horizontal camera to target distance using the trailer backup system **105**. The method will be described below as being implemented by the controller **2010**. As such, this method may be a routine executed by any processor (e.g., processor **2030**), and thus this method may be embodied in a non-transitory computer readable medium having stored thereon software instructions that, when executed by a processor, cause the processor to carry out its intended functionality.

With reference to FIGS. **49-51**, the method will be described in which the controller **2010** calculates a horizontal camera to target distance  $d_h$ . To do so, the controller **2010** is supplied with a user-obtained measurement entered through the input device **2005** and can additionally use image data from the camera **2000** and known camera and/or vehicle related parameters that can be stored in memory (e.g., memory **2035**) and accessible to the controller **2010**. While implementing the method, certain assumptions are made with regard to parameters associated with the vehicle **2015** and trailer **2025**. Examples of such assumptions include, but are not limited to, the target **2020** being disposed on the trailer **2025** such that the target **2020** is capable of being detected by the camera **2000**, the camera **2000** being located at a position above the target **2020**, and the vehicle **2015** and the trailer **2025** being properly aligned with one another.

With respect to the illustrated embodiment, the camera is exemplarily shown coupled to a rear member **2038** (i.e. tailgate) of the vehicle **2015** and the target **2020** is positioned longitudinally across a tongue portion **2040** of the trailer **2025**. In the illustrated embodiment, the camera **2000** has a vertical field of view defined by an upper field extent **2045** and a lower field extent **2050** for imaging a rear vehicle area that includes the target **2020**. To determine the horizontal camera to target distance  $d_h$  using the method described herein, the controller **2010** calculates a first horizontal distance  $d_1$  and a second horizontal distance  $d_2$  that are summed together to yield the horizontal camera to target distance  $d_h$ .

The first horizontal distance  $d_1$  corresponds to a horizontal distance from the camera **2000** to an intersection point  $p_i$

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between the lower field extent of the vertical field of view and a centerline longitudinal axis X of the target **2020**, and is expressed by equation 1:

$$d_1 = d_v \tan \theta$$

where,

$d_h$ : horizontal camera to target distance;

$d_1$ : first horizontal distance;

$d_2$ : second horizontal distance;

$d_v$ : vertical camera to target distance;

$\theta$ : a known angle between a vertical extent Y of the rear member **2038** of the vehicle **2015** and the lower field extent **2050** of the vertical field of view of camera **2000**;

$t_g$ : target to ground distance;

$r_h$ : known receiver height;

$d_m$ : draw bar drop measurement;

$p_i$ : intersection point;

$p_m$ : target midpoint.

To calculate the vertical camera to target distance  $d_v$ , it is preferable for the user to measure a target to ground distance  $t_g$ , which can be supplied to the controller **2010** via the input device **2005**. Alternatively, in some cases, the controller **2010** can estimate the target to ground distance  $t_g$  within an acceptable tolerance by using a known receiver height  $r_h$  for the target to ground distance  $t_g$  value in instances where a straight draw bar **2055** is used. In instances where the draw bar **2055** has a drop, the controller **2010** can be supplied with a draw bar drop measurement  $d_m$ , which is typically known to the user, and estimates the target to ground distance  $t_g$  by subtracting the draw bar drop measurement  $d_m$  from the receiver height  $r_h$  (see FIG. **52**). It should be appreciated that the draw bar drop measurement  $d_m$  can be supplied to the controller **2010** in a variety of manners. For example, the draw bar drop measurement  $d_m$  can be manually entered via the input device **2005**. In instances where a barcode or other machine readable code is provided on the draw bar **2055**, it is possible to use the camera **2000** or a portable electronic device equipped with a camera (e.g., a smartphone) to perform optical character recognition (OCR) to identify the particular draw bar model and automatically import the draw bar drop measurement  $d_m$  to the trailer backup assist system **105**. In any event, once the target to ground distance  $t_g$  has been determined, the controller **2010** subtracts the target to ground distance  $t_g$  from a known camera to ground distance  $c_g$  to calculate the vertical camera to target distance  $d_v$ . By virtue of angle  $\theta$  being known, the controller **2010** can now calculate the first horizontal distance  $d_1$  using equation 1.

Once the first horizontal distance  $d_1$  has been calculated, the controller **2010** next calculates the second horizontal distance  $d_2$ , which corresponds to a distance from the intersection point  $p_i$  to a target midpoint  $p_m$ , and is expressed by equation 2:

$$d_2 = \sqrt{d_a^2 + d_b^2 - 2d_a d_b \cos \gamma}$$

where,

$d_a$ : camera to intersection point distance;

$d_b$ : camera to target midpoint distance;

$\gamma$ : angle between the camera to target midpoint distance  $d_b$  and the camera to intersection point distance  $d_a$ .

Having previously calculated the vertical camera to target distance  $d_v$  and the first horizontal distance  $d_1$ , the camera to intersection point distance  $d_a$  can be calculated using the Pythagorean Theorem.

Angle  $\gamma$  may be calculated by observing a relationship between the vertical field of view and a corresponding camera image. This relationship is shown by equation 3:

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$$\frac{\gamma}{\delta} = \frac{p_c}{v_r}$$

where,

$\delta$ : vertical field of view angle;

$p_c$ : pixel count taken from the lower field extent to the target midpoint  $p_m$  with respect to camera image **2060**, as shown in FIG. **53**;

$v_r$ : vertical resolution of the camera image **2060**.

Pixel count  $p_c$  can be determined using any suitable image recognition method and naturally varies based on the positioning of the target **2020**. The vertical field of view angle  $\delta$  and the vertical resolution  $v_r$  are each typically known from the camera **2000** specification and the corresponding values can be stored to memory (e.g., memory **2035**) and supplied to the controller **2010** in any suitable manner. Once the controller **2010** receives the pixel count  $p_c$ , vertical field of view angle  $\delta$ , and vertical resolution  $v_r$ , equation 3 can be solved to calculate angle  $\gamma$ .

Camera to target midpoint distance  $d_b$  can be calculated using equation 4:

$$d_b = \frac{d_v}{\sin \alpha}$$

where,

$d_v$ : vertical camera to target distance;

$\alpha$ : angle between the camera to target midpoint distance  $d_b$  and the centerline longitudinal axis X of the target.

By recognizing that the vertical camera to target distance  $d_v$  is perpendicular with the centerline longitudinal axis X, angle  $\alpha$  can be calculated by subtracting 90 degrees, angle  $\delta$ , and angle  $\gamma$  from 180 degrees. Having done this, the camera to target midpoint distance  $d_b$  can be calculated using equation 4, which allows for the second horizontal distance  $d_2$  to be calculated using equation 2. Finally, the horizontal camera to target distance  $d_h$  can be calculated by summing together the first horizontal distance  $d_1$  and the second horizontal distance  $d_2$ .

#### Modified Control for Trailer Backup Assist System

It is disclosed herein that a trailer backup assist system **105** may be implemented to operate a vehicle **100** attached to a trailer **110** for controlling the curvature of the trailer **110** when executing a backup maneuver. As previously described, kinematic information (FIG. **36**) of the attached vehicle and trailer are used to calculate a relationship between the trailer's curvature and the steering angle of the vehicle for determining a steering angle command of the vehicle that will achieve the desired trailer path. According to some of the previously described control system embodiments for the trailer backup assist system **105**, the kinematic relationship had less desirable results for hitch connections with gooseneck trailers, such as those configured to attached to a hitch ball in a truck bed or configured with a kingpin to attach to a fifth wheel connector on a vehicle.

Referring now to FIGS. **54-61D**, a trailer backup assist system **105** may be modified from the embodiments described above for operation with a trailer **110** that has a gooseneck tongue, commonly referred to as a gooseneck trailer **1500**, or other trailers having a pivoting connection **117** with a vehicle **100** near or at a rear axle **1502** of the vehicle **100**. In one such embodiment, the trailer backup assist system **105** includes a hitch sensor **1504** that senses a measured hitch angle  $\gamma(m)$  between the vehicle **100** and the trailer **110**. A

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steering sensor **140** may also be provided for sensing a steering angle  $\delta$  of the vehicle. Also, the trailer backup assist system **105** may include a curvature input module **1506** that receives the desired curvature  $\kappa_2$  of the trailer **110**. A controller **1508** is then provided that generates a steering angle command for the vehicle as a function of the measured hitch angle  $\gamma(m)$ , the steering angle  $\delta$ , and the desired curvature  $\kappa_2$  of the gooseneck trailer **1500**.

According to one embodiment of the trailer backup assist system **105**, the controller **1508** may be configured with a curvature regulator **1510** and a hitch angle regulator **1512**, whereby the curvature regulator **1510** determines a desired hitch angle  $\gamma(d)$  based on the desired curvature  $\kappa_2$  and the steering angle  $\delta$ . In conjunction with operation of the curvature regulator **1510**, the hitch angle regulator **1512** generates the steering angle command based on the desired hitch angle  $\gamma(d)$  computed by the curvature regulator **1510** and the measured hitch angle  $\gamma(m)$  determined by the hitch sensor **1504**. In an additional embodiment of the controller **1508**, an assumption may be made that a longitudinal distance between the pivoting connection **117** and the rear axle **1502** of the vehicle **100** is equal to zero for purposes of the curvature control system of the trailer backup assist system **105** when a gooseneck trailer **1500** or other similar trailer is connected with the a hitch ball or a fifth wheel connector on the vehicle **100**. The assumption essentially assumes that the pivoting connection with the trailer **110** is substantially aligned with the rear axle **1502**. When such an assumption is made, the controller **108** may generate the steering angle command for the vehicle **100** as a function independent of the distance, L, between the pivoting connection **117** and the rear axle **1502** of the vehicle **100**. These and other embodiments of the controller **1508** for the trailer backup assist system **105** are described in greater detail herein.

Referring now to FIG. **54**, an exemplary embodiment of a vehicle **100** having the trailer backup assist system **105** is illustrated coupled with one embodiment of a gooseneck trailer **1500**. The gooseneck trailer **1500** shown has a flatbed cargo area **1514** supported with a pair of axles **1516**, whereby a tongue **1518** protrudes upward from the flatbed cargo area **1514** and forward into a bed **1520** of the vehicle **100** to pivotally attach to the vehicle **100** proximate the rear axle **1502** of the gooseneck trailer **1500**. The bed of the vehicle may be provided with a hitch ball that is configured to form a pivoting connection **117** with a corresponding coupler assembly on the tongue **1518** of the gooseneck trailer **1500**. Alternatively, the bed **1520** of the vehicle **100** may be provided with a fifth wheel connector that is configured to form a pivoting connection **117** with a kingpin on the tongue **1518** of the gooseneck trailer **1500**. In the illustrated embodiment, the pivoting connection **117** is positioned to align with the rear axle **1502** of the vehicle **100**, such that the longitudinal distance L between the rear axle and the pivoting connection **117** is equal to zero. It is contemplated that in additional embodiments the pivoting connection **117** may be formed with other coupling assemblies to form a hitch pivot point, defined by a generally vertical axis, substantially aligned with the rear axle **1502** of the vehicle **100**, which may be slightly forward or rearward from the rear axle **1502**. It is also appreciated that the gooseneck trailer **1500** described herein is generally referring to the tongue configuration being elevated to attach with the vehicle **100** at an elevated location over the rear axle **1502**, such that other embodiments of the gooseneck trailer **1500** include enclosed cargo areas, campers, cattle trailers, horse trailers, lowboy trailers, and other conceivable trailers with such a tongue configuration.

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As illustrated in FIG. 55, one embodiment of the trailer backup assist system 105 is depicted to include a hitch angle detection apparatus 130, which may operate in conjunction with at least one hitch angle sensor 1312 to provide the controller 1508 with information relating to a hitch angle  $\gamma$  between the vehicle and the trailer. As previously described, the hitch angle detection apparatus 130 may include various systems that incorporate one or more physical sensors on the vehicle 100 and/or the trailer 110 in combination with computing other vehicle and trailer dimensions and characteristics (i.e. kinematic information) to otherwise determine a measured hitch angle  $\gamma(m)$  between the vehicle 100 and the trailer 110. Similarly, the hitch angle sensor 1312 may include various types of sensors, including a vision based sensor system, a magnetic sensor system, a capacitive sensor system, an inductive sensor system, and other conceivable sensors and combinations thereof. Further, the hitch sensor 1504 of the embodiment of the trailer backup assist system 105 shown in FIG. 55 and referenced in this section may include the hitch angle detection apparatus 130, the hitch angle sensor 1312, or a combination of both for sensing the hitch angle  $\gamma$  between the vehicle 100 and the trailer 110.

With continued reference to FIG. 55, the controller 1508 of the trailer backup assist system communicates with a power steering assist system 115 in operating the embodiment of the trailer backup assist system 105 described herein. More specifically, a steering angle detection apparatus (or steering sensor) 140 of the power steering assist system 115 may be used for sensing a steering angle  $\delta$  of the steered wheels 1302 (FIG. 36) of the vehicle 100. The power steering assist system 115 may also receive the steering angle command generated by the controller 1508 for autonomously steering the vehicle 100 or otherwise altering the steering angle  $\delta$  of the vehicle 100. The controller 1508 also receives information from a vehicle speed sensor 1316, which may be incorporated with an onboard sensor system of the vehicle 100 or an auxiliary device, such as a portable GPS unit or smart phone.

As shown in FIG. 55, the illustrated embodiment of the trailer backup assist system 105 also includes a curvature input module 1506 to provide the controller 1508 with information defining a desired or commanded path of travel of the trailer, such as providing a desired curvature  $\kappa_2$  of the trailer 110. The desired curvature  $\kappa_2$  may equate to a ratio of one over a radius  $r_2$  (FIG. 36) of the desired path rearward from the trailer 110, which when the radius equals zero would correspond with a substantially straight path of travel. Accordingly, the information provided by the curvature input module 1506 can include information relating to a commanded change in the curvature  $\kappa_2$  and information relating to an indication that the trailer 110 is to travel along a path defined by a longitudinal centerline axis of the trailer 110 (i.e., along a substantially straight path of travel). According to one embodiment, the curvature input module 1506 may be a trajectory planner that generates a curvature  $\kappa_2$  for the trailer to reach a desired waypoint position, as disclosed in greater detail below.

According to another embodiment, as shown in FIG. 56, the curvature input module 1506 includes the trailer backup steering input apparatus 125, which has a rotational control input device for allowing a driver of the vehicle 100 to command desired trailer steering actions. In the illustrated embodiment, the rotational control input device is a knob 170 (FIG. 2) rotatable about a central axis between a middle position 1522 corresponding to a substantially straight path of travel, as defined by a longitudinal centerline axis of the trailer 110, and various rotated positions 1524, 1526, 1528, 1530 on opposing sides of the middle position 1522, com-

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manding a desired curvature  $\kappa_2$  corresponding to a radius of the desired path of travel of the trailer 110 at the rotated position. It is also contemplated that the curvature input module 1506 may incorporate multiple sources, such as a trajectory planner, a rotational control input device, and an override input device or other source to provide a desired curvature  $\kappa_2$  value to the controller 1508.

One embodiment of the controller 1508 of the trailer backup assist system 105 is illustrated in FIG. 57, showing the general architectural layout of one embodiment. In the illustrated layout, the curvature input module 1506 provides a desired curvature  $\kappa_2$  value to the curvature regulator 1510 of the controller 1508. The curvature regulator 1510 computes a desired hitch angle  $\gamma(d)$  based on the current desired curvature  $\kappa_2$  along with the steering angle  $\delta$  provided by a measurement module 1532 in this embodiment of the controller 1508. The measurement module 1532 may be a memory device separate from or integrated with the controller 1508 that stores data from sensors of the trailer backup assist system 105, such as the hitch angle sensor 1504, the vehicle speed sensor 1316, the steering sensor 140, or alternatively the measurement module 1532 may otherwise directly transmit data from the sensors without functioning as a memory device. Accordingly, the measured steering angle  $\delta$  may be provided by the steering sensor 140 as shown in FIG. 55 or may be a value derived from a function utilizing other kinematic information of the vehicle.

With further reference to FIG. 57, once the desired hitch angle  $\gamma(d)$  is computed by the curvature regulator 1510 the hitch angle regulator 1512 generates a steering angle command based on the computed desired hitch angle  $\gamma(d)$  as well as a measured hitch angle  $\gamma(m)$  and a current velocity of the vehicle 100. The steering angle command is supplied to the power steering assist system 115 of the vehicle 100, which is then fed back to the measurement module 1532 to reassess the impacts of other vehicle characteristics impacted from the implementation of the steering angle command or other changes to the system 105. Accordingly, the curvature regulator 1510 and the hitch angle regulator 1512 continually process information from the measurement module 1532 to provide accurate steering angle commands that place the trailer 110 on the desired curvature  $\kappa_2$  without substantial overshoot or continuous oscillation of the path of travel about the desired curvature  $\kappa_2$ .

As shown in FIG. 58, one embodiment of the controller 1508 is illustrated in a control system block diagram. Specifically, entering the control system is an input,  $\kappa_2$ , which represents the desired curvature of the trailer 110 that is provided to the curvature regulator 1510. The curvature regulator can be expressed as a static map,  $p(\kappa_2, \delta)$ , which in one embodiment is the following equation:

$$p(\kappa_2, \delta) = \tan^{-1} \left( \frac{\kappa_2 D + L \tan(\delta)}{\kappa_2 D L \tan(\delta) - W} \right)$$

Where,

$\kappa_2$  represents the desired curvature of the trailer or  $1/r_2$  as shown in FIG. 36;

$\delta$  represents the steering angle;

L represents the distance from the rear axle of the vehicle to the hitch pivot point;

D represents the distance from the hitch pivot point to the axle of the trailer; and

W represents the distance from the rear axle to the front axle of the vehicle.

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With further reference to FIG. 58, the output hitch angle of  $p(\kappa_2, \delta)$  is provided as the reference signal,  $\gamma_{ref}$  for the remainder of the control system, although the steering angle  $\delta$  value used by the curvature regulator 1510 is feedback from the non-linear function of the hitch angle regulator 1512. It is shown that the hitch angle regulator 1512 uses feedback linearization for defining a feedback control law, as follows:

$$g(u, \gamma, v) = \delta = \tan^{-1} \left( \frac{W}{v \left( 1 + \frac{L}{D} \cos(\gamma) \right)} \left( u - \frac{v}{D} \sin(\gamma) \right) \right)$$

As also shown in FIG. 58, the feedback control law,  $g(u, \gamma, v)$ , is implemented with a proportional integral (PI) controller, whereby the integral portion substantially eliminates steady-state tracking error. More specifically, the control system illustrated in FIG. 58 may be expressed as the following differential-algebraic equations:

$$\dot{\gamma}(t) = \frac{v(t)}{D} \sin(\gamma(t)) + \left( 1 + \frac{L}{D} \cos(\gamma(t)) \right) \frac{v(t)}{W} \delta$$

$$\tan(\delta) =$$

$$\delta = \frac{W}{v(t) \left( 1 + \frac{L}{D} \cos(\gamma(t)) \right)} \left( K_P (p(\kappa_2, \delta) - \gamma(t)) - \frac{v(t)}{D} \sin(\gamma(t)) \right)$$

It is contemplated that the PI controller may have gain terms based on trailer length  $D$  since shorter trailers will generally have faster dynamics. In addition, the hitch angle regulator 1512 may be configured to prevent the desired hitch angle  $\gamma(d)$  to reach or exceed a jackknife angle  $\gamma(j)$ , as computed by the controller or otherwise determined by the trailer backup assist system 105, as disclosed in greater detail above.

Referring now to FIG. 59, a method for operating the trailer backup assist system 105 is illustrated according to one embodiment. The method provides an initial step 1534 of sensing a measured hitch angle  $\gamma(m)$  between the vehicle 100 and the trailer 110. Either before, after, or concurrently with sensing the measured hitch angle  $\gamma(m)$ , at step 1536 a steering angle  $\delta$  of the vehicle 100 is sensed, such as with the steering sensor 140 shown in FIG. 55. With the trailer 110 attached and ready to reverse, a desired curvature  $\kappa_2$  of the trailer 110 is received at step 1538. In one embodiment, a trajectory planner may be used to generate a path for the trailer 110 to determine desired curvature  $\kappa_2$  for the trailer 110. At step 1540 of the method, a desired hitch angle  $\gamma(d)$  is determined based on the desired curvature  $\kappa_2$  and the steering angle  $\delta$ . In one embodiment, at step 1542, a jackknife angle  $\gamma(j)$  may be determined based on a length  $D$  of the trailer 110, as previously explained with reference to FIGS. 5 and 7, and thereby used to prevent the desired hitch angle  $\gamma(d)$  from exceeding the jackknife angle. Using feedback linearization, at step 1544 a steering angle command for the vehicle may be generated based on the desired hitch angle  $\gamma(d)$ , the measured hitch angle  $\gamma(m)$ , and a velocity of the vehicle. This controller implementing step 1544 is configured to generate the steering angle command consistent with the desired curvature  $\kappa_2$  when a gooseneck trailer 1500 is attached to the vehicle 100, such that a distance,  $L$ , defined longitudinally between a rear axle 1502 of the vehicle 100 and a pivoting connection 117

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between the vehicle 100 and the trailer 110 is greater than or substantially equal to zero. Accordingly, with the steering angle commands generated by the trailer backup assist system 105, at step 1546, the power steering assist system 115 of the vehicle 100 is operated to steer the vehicle 100 and thereby move the trailer 110 in compliance with the desired curvature  $\kappa_2$ .

With respect to operation of the trailer backup assist system 105, FIGS. 60A-60D depict experimental data of a vehicle using the trailer backup assist system 105 to reverse a gooseneck trailer in a single backup maneuver with a constant curvature input. As shown in FIG. 60A, the desired curvature  $\kappa_2$  is plotted against the observed curvature over time of operating the backup maneuver, showing the observed curvature closely following the desired curvature  $\kappa_2$ , substantially similar to the correlation between the measured hitch angle  $\gamma(m)$  and the commanded or desired hitch angle  $\gamma(d)$  shown in FIG. 60B. The corresponding steering angle  $\delta$  and velocity of the vehicle 100 for the data shown in FIGS. 60A-B is plotted over the same time interval in FIGS. 60C-D. In addition, FIGS. 61A-61D depict an alternative set of experimental data of a vehicle using the trailer backup assist system 105 to reverse a conventional trailer. Similar to the results with the gooseneck trailer, FIGS. 61A-B show how the observed curvature and the measured hitch angle  $\gamma(m)$  closely follows the desired curvature  $\kappa_2$  and the desired hitch angle  $\gamma(d)$  as the system responds to the change in input desired curvature  $\kappa_2$  shown in FIG. 61A. Again, the corresponding steering angle  $\delta$  and velocity of the vehicle 100 for the data shown in FIGS. 61A-B is plotted over the same time interval in FIGS. 61C-D, which also substantially correlates with the steering angle  $\delta$  and velocity of the vehicle 100 shown in FIGS. 60C-D. Accordingly, this data further demonstrates that the controller 1508 (FIG. 55) provides substantially similar control of the trailer using the trailer backup assist system 105 with both gooseneck trailers and conventional trailers. The illustrated experimental data is exemplary of one embodiment of operating the trailer backup assist system 105, such that more refinements through tuning may be realized in further implementation of the trailer backup assist system 105.

#### Trajectory Planning for a Trailer Backup Assist System

As referenced above, a trailer backup assist system 105 may be implemented with a curvature input module 1506 to control the curvature of the trailer 110 when executing a backup maneuver with a vehicle 100 attached to the trailer 110. In several of the previously described embodiments, the curvature input module 1506 may include a manually operable knob to provide the desired curvature  $\kappa_2$  to a controller in substantially real time. In an additional embodiment, as disclosed in greater detail below, a trajectory planner 1550 is provided for the curvature input module 1506 to similarly provide the desired curvature  $\kappa_2$  to the controller in substantially real time for operating the vehicle 100. Although in one embodiment it is contemplated that the trajectory planner 1550 may be the exclusive source of providing the desired curvature  $\kappa_2$ , it is understood that in additional embodiments a rotatable knob or other human-machine interface may be used in conjunction with the trajectory planner 1550 to manually adjust or override the desired curvature  $\kappa_2$  provided by the trajectory planner 1550.

As previously referenced, kinematic information (FIG. 36) of the attached vehicle 100 and trailer 110 may be used to calculate a relationship between the trailer's curvature and the steering angle  $\delta$  of the vehicle 100 for determining a steering angle command of the vehicle 100 that will achieve the desired curvature  $\kappa_2$  received from the curvature input mod-

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ule **1506**. More specifically, when certain assumptions are made, including the variables  $D$  and  $W$  being greater than zero and the velocity of the vehicle **100** being greater than zero, the trailer angle kinematics in one embodiment can be expressed as follows:

$$\dot{\gamma} = \frac{v}{D} \sin(\gamma) + \left(1 + \frac{L}{D} \cos(\gamma)\right) \frac{v}{W} \tan(\delta).$$

Also, the velocity of the trailer's center of mass may be given by the following equation:

$$v_T = v \cos(\gamma) - \frac{vL}{W} \sin(\gamma) \tan(\delta).$$

Combining these equations, the curvature  $\kappa_2$  of the trailer trajectory, corresponding to  $1/r_2$ , can be calculated as the ratio between the angular velocity of the trailer **110** and trailer velocity, which provides the following curvature  $\kappa_2$  algorithm:

$$\kappa_2 = \frac{\dot{\theta}}{v_T} = -\frac{W \sin(\gamma) + L \cos(\gamma) \tan(\delta)}{D(W \cos(\gamma) - L \sin(\gamma) \tan(\delta))}.$$

According to one embodiment of the trailer backup assist system **105**, the curvature input module **1506** provides the desired curvature  $\kappa_2$  of the trailer **110** to a curvature controller **1508** for generating the steering angle command for the vehicle **100** based on a current steering angle  $\delta$  of the vehicle and a measured hitch angle  $\gamma(m)$  between the vehicle **100** and the trailer **110**. As such, one embodiment of the curvature controller **1508** may operate with the following control system, where  $\kappa_2$  represents the curvature input signal:

$$\begin{aligned} \dot{\gamma}(t) &= \frac{v(t)}{D} \sin(\gamma(t)) + \left(1 + \frac{L}{D} \cos(\gamma(t))\right) \frac{v(t)}{W} \delta; \\ \tan(\delta) &= \bar{\delta} = \frac{W}{v(t) \left(1 + \frac{L}{D} \cos(\gamma(t))\right)} \left(K_P(p(\kappa_2, \delta) - \gamma(t)) - \frac{v(t)}{D} \sin(\gamma(t))\right); \\ \text{and} \\ p(\kappa_2, \delta) &= \tan^{-1} \left( \frac{\kappa_2 D W + L \tan(\delta)}{\kappa_2 D L \tan(\delta) - W} \right). \end{aligned}$$

Referring to FIGS. **62-72B**, reference numeral **1550** generally designates a trajectory planner for a trailer backup assist system **105**. According to one embodiment, the trailer backup assist system **105** includes a state estimator **1552** that determines a current position of the trailer **110** relative to a waypoint position. The trajectory planner **1550** generates first and second circular trajectories **1554**, **1556** tangent to one another spanning between the current position and the waypoint position. A curvature controller **1508** reverses the trailer **110** to the waypoint position along the first and second circular trajectories **1554**, **1556**, which are dynamically regenerated as the trailer **110** reverses along the first circular trajectory **1554**.

According to a further embodiment, the trajectory planner **1550** for reversing a trailer **110** with a trailer backup assist system **105** may include a first operating mode **1558** dynamically generating the first and second circular trajectories

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**1554**, **1556** tangent to one another that connect between the current position of the trailer **110** and the waypoint position as the trailer **110** reverses along the first circular trajectory **1554**. The trajectory planner **1550** may also include a second operating mode **1560** dynamically generating the second circular trajectory **1556** to the waypoint position as the trailer **110** reverses along the second circular trajectory **1556**. It is also contemplated that a third operating mode **1562** may be included that switches to the first operating mode when the trailer **110** reaches the waypoint for guidance to a subsequent waypoint of a plurality of waypoints. These and other potential planner modes **1564** will be described in greater detail below, as they refer to guiding the trailer **110** to a single waypoint or a plurality of waypoints.

Referring now to FIG. **62**, the trailer backup assist system **105** of the illustrated embodiment includes a hitch angle detection apparatus **130**, which may operate in conjunction with at least one hitch angle sensor **1312** to provide information relating to a hitch angle  $\gamma$  between the vehicle **100** and the trailer **110**. As previously described, the hitch angle detection apparatus **130** may include various systems that incorporate one or more physical sensors on the vehicle **100** and/or the trailer **110** in combination with computing other vehicle and trailer dimensions and characteristics (i.e. kinematic information) to otherwise determine a measured hitch angle  $\gamma(m)$  between the vehicle **100** and the trailer **110**. Similarly, the hitch angle sensor **1312** may include various types of sensors, including a vision based sensor system, a magnetic sensor system, a capacitive sensor system, an inductive sensor system, and other conceivable sensors and combinations thereof. Further, the hitch sensor **1504** of the embodiment of the trailer backup assist system **105** may include the hitch angle detection apparatus **130** for providing the measured hitch angle  $\gamma(m)$  to the state estimator **1552** of the illustrated embodiment of the trailer backup assist system **105**. Also, the trailer backup assist system **105** may include the power steering assist system **115** with a steering sensor **140** for sensing a steering angle  $\delta$  of the steered wheels **1302** (FIG. **36**) of the vehicle **100**. The power steering assist system **115** may also receive the steering angle command generated by the controller **1508** for autonomously steering the vehicle **100** or otherwise altering the steering angle  $\delta$  of the vehicle **100**.

As also shown in the embodiment illustrated in FIG. **62**, the state estimator **1552** receives positioning information from a positioning device **1566** as well as hitch angle information from the hitch sensor **1504** to determine the current position of the trailer **110**. Accordingly, it is understood that the current and waypoint positions each include a coordinate location and an angular orientation (i.e. a tuple). Accordingly, the state estimator **1552** may determine the current position of the trailer **110** based on the hitch angle  $\gamma(m)$  sensed between the trailer **110** and the vehicle **100** and a coordinate position of the vehicle **100**. As such, the coordinate position of the vehicle **100** provided by the positioning device **1566** in the illustrated embodiment may be generated from a localized coordinate system generated proximate the waypoint position, whereby steering information and velocity of the vehicle **100** may be used to track the coordinate position, including the coordinate location and angular orientation, of the vehicle **100** relative to the localized coordinate system. In another embodiment, the positioning device **1566** may additionally or alternatively include a global positioning system (GPS) receiver **1568** that provides a coordinate position of the vehicle **100**, which may be identifiable relative to the waypoint position, if also configured with a GPS-based coordinate position. In an alternative embodiment, the state estimator **1552** may simply determine the current position of the trailer **110** based on a

coordinate position of the trailer 110, if such information available, for example via a GPS receiver located directly on the trailer 110.

With further reference to FIG. 62, it is shown that in addition to supplying the curvature controller 1508 with the current position of the trailer, the state estimator 1552 also provides the trajectory planner 1550 of the curvature input module 1506 with the current position of the trailer 110. As previously mentioned, the trajectory planner 1550 may provide a desired curvature  $\kappa_2$  signal to the curvature controller 1508 that is indicative of a curvature  $\kappa_2$  corresponding to a path between the current position of the trailer 110 and a waypoint position.

As shown in more detail in FIG. 63, one embodiment of the trajectory planner 1550 is shown in a controller layout, whereby the trajectory planner 1550 receives the current position from the state estimator 1552. In addition, the trajectory planner 1550 receives information from communicating with a vehicle human-machine interface (HMI) 25. It should be appreciated that the trajectory planner 1550 may be a standalone dedicated controller or may be a shared controller integrated with other control functions, such as integrated with the curvature controller 1508 or another controller of the trailer backup assist system 105. It is contemplated that the vehicle HMI 25 may transmit a desired waypoint position or a plurality of waypoint positions to the trajectory planner 1550. For instance, the vehicle HMI 25 may include a center stack mounted display, such as a touch screen display, that allows a user to input a waypoint position relative to the current position of the vehicle 100. It also is contemplated that the waypoint positions or one or more of the plurality of waypoint positions may be generated by the trajectory planner 1550 or a separate controller. Accordingly, the waypoint positions received by the trajectory planner 1550 may thereby be stored in memory 1570 of the trajectory planner 1550, such as within a waypoint module 1572, for processing with a microprocessor 1574 of the trajectory planner 1550 in conjunction with the planner modes 1564 to provide the desired curvature  $\kappa_e$  to the curvature controller 1508.

Referring to FIG. 64, the trajectory planner 1550 is schematically shown in a control system layout, according to one embodiment, whereby the curvature controller 1508 outputs a steering angle  $\delta$ , or a necessary change in the steering angle  $\delta$ , that is provided as feedback to the state estimator 1552 for resolving errors in operation of the trailer backup assist system 105, according to this embodiment. In addition to the steering angle  $\delta$ , the curvature controller 1508 may also output a hitch angle  $\gamma$ , as described with reference to FIG. 58. As also shown in FIG. 64, the waypoint position information may be provided to the trajectory planner 1550 and stored in the waypoint module 1572 for processing with the planner modes 1564 (FIG. 63).

When a single waypoint position in the waypoint module 1572 is processed by the trajectory planner 1550, an embodiment of the planner modes 1564 may be used to provide a curvature  $\gamma_2$  output for executing a backup maneuver to the single waypoint position, as illustrated in FIG. 65. More specifically, once the waypoint position is identified, a first operating mode 1558 generates first and second circular trajectories 1554, 1556 tangent to one another that connect between the current position of the trailer 110 and the waypoint position, as depicted in FIG. 66. With respect to notation for the first operating mode 1558, the current position of the trailer 110 is represented as the current coordinate location  $x=(x_1, x_2)$ , longitude and latitude, respectively, with the current angular orientation  $\phi^x$ ; while the waypoint position is represented as a coordinate location of  $T=(T_1, T_2)$  with an

angular orientation  $\phi^T$ . The radii of the first and second circular trajectories 1554, 1556 are represented by  $r^x$  and  $r^T$ , respectively, and the corresponding curvatures of the first and second circular trajectories 1554, 1556 can thereby be represented as  $\kappa^x=1/r^x \in [-\kappa_{min}, \kappa_{max}]$  and  $\kappa^T=1/r^T \in [-\kappa_{min}, \kappa_{max}]$ , respectively. The referenced curvature constraints may be calculated based on the kinematic information of the particular vehicle 100 and trailer 110 combination to avoid a jack-knife hitch angle. Given the current position  $(x, \phi^x)$  and the waypoint position  $(T, \phi^T)$ , the corresponding circles  $C^x$  and  $C^T$  with center points  $c^x$  and  $c^T$  can be defined as:

$$c^x = x + r^x (-\sin(\phi^x), \cos(\phi^x));$$

$$C^x = \{z \in R^2 \mid \|z - c^x\| = r^x\};$$

$$c^T = T + r^T (-\sin(\phi^T), \cos(\phi^T)); \text{ and}$$

$$C^T = \{z \in R^2 \mid \|z - c^T\| = r^T\},$$

where, arc segments of the path of travel on the first and second circular trajectories 1554, 1556 are identified as  $\partial C^x$  and  $\partial C^T$ , respectively.

With further reference to FIGS. 65-66, the first operating mode 1558 generates the first and second circular trajectories 1554, 1556 tangent to one another connecting between the current and waypoint positions, such that the first and second circular trajectories 1554, 1556 are tangent to the angular orientation at the respective current position and waypoint position. The first and second circular trajectories 1554, 1556 are generated tangent to one another to define a tangent position,  $z \in R^2$ , between the first and second circular trajectories 1554, 1556. To generate the first and second circular trajectories 1554, 1556 with these curvatures constraints, a solution set can be represented as follows:

$$R((x, \phi^x), (T, \phi^T)) = \{(\kappa^x, \kappa^T) \in [\kappa_{min}, \kappa_{max}]^2 \mid C^x \cap C^T = z \in R^2\}.$$

As shown in FIGS. 67A-B, in instances where the limitations of  $\kappa_{min}, \kappa_{max}$  do not prohibit a solution, the solution set of  $R((x, \phi^x), (T, \phi^T))$  theoretically has an infinite number of first and second circular trajectories 1554, 1556 tangent to one another connecting between the current position and the waypoint position, including those that have arc segments of the path of travel that may bypass the waypoint position and/or encompass the majority of the circular circumference of a circular trajectory. Accordingly, the first operating mode 1558 includes a cost function to identify a single path of the solution set, defining the first and second circular trajectories 1554, 1556 for purposes of operation. In one embodiment, the cost function will penalize the size of the curvatures  $\kappa^x$  and  $\kappa^T$ , the arc lengths  $\partial C^x$  and  $\partial C^T$ , and the difference between the curvatures  $\kappa^x$  and  $\kappa^T$ . As such, the cost function will seek to identify the single path of the solution set that has both a relatively short distance and has a relatively small amount of curvature. However, it is contemplated that a cost function in additional embodiments may be constructed to penalize the curvature and arc length variables alternatively or constructed to penalize more or fewer variables in identifying a single path. To implement a cost function, the identified single path will be defined as the solution to the following algorithm:

$$(\hat{\kappa}^x, \hat{\kappa}^T) = \arg \inf_{(\kappa^x, \kappa^T) \in R((x, \phi^x), (T, \phi^T))} L(\kappa^x, \kappa^T).$$

First, computing the plurality of potential pairs of tangent circular trajectories between the current and waypoint positions, as defined by  $R((x, \phi^x), (T, \phi^T))$  may be done by identifying the geometric relationship of the first and second circular trajectories 1554, 1556, as shown in FIG. 66, which shows a dashed line connecting the circle center points  $c^x$  and  $c^T$ . This geometric relationship may be exploited to solve for

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$r^T$  based on angles  $\alpha$  and  $\beta$ , as shown in FIG. 36. In view of the solution for  $r^T$ , the cost function, according to one embodiment, can have a weighing vector  $k=[k_1, k_2, k_3, k_4, k_5]$ , which is then recited as follows:

$$L(\kappa^x, \kappa^T) = k_1 |\kappa^x| + k_2 |\kappa^T| + k_3 \partial C^x + k_4 \partial C^T + k_5 |\kappa^x - \kappa^T|.$$

To reiterate, the first operating mode 1558 of the trajectory planner 1550 provides the desired curvature  $\kappa_2$  to the curvature controller 1508, which in consideration of the cost function, may be expressed as the following function:

$$\kappa_2 = \hat{\kappa}^x = \text{CircToCirc}(x, T, \phi^x, \phi^T).$$

As the vehicle 100 guides the trailer 110 on the first circular trajectory 1554, the first and second circular trajectories 1554, 1556 are continuously and therefore dynamically regenerated to account for changes in the current position of the trailer 110 outside of the previously generated first circular trajectory 1554.

Referring again to FIG. 65, the trajectory planner 1550 processes the first operating mode 1558 until the trailer 110 reaches the tangent position  $z$  (FIG. 66), at which point the trajectory planner 1550 switches from guiding the trailer 110 along the first circular trajectory 1554 to guiding the trailer 110 along the second circular trajectory 1556 to the waypoint position. Accordingly, when the trailer 110 reaches the tangent position  $z$ , the trajectory planner 1550 switches from the first operating mode 1558 to the second operating mode 1560 for guiding the trailer along the second circular trajectory 1556. The trajectory planner 1550 processes a switching routine to make the determination when to stop processing the first operating mode 1558 and start processing the second operating mode 1560. Therefore, in one embodiment, it is contemplated that the switching routine may be part of the first operating mode 1558. The switching routine, according to one embodiment, computes the distance between the current position and the center point  $c^T$  of the second circular trajectory 1556 and switches to the second operating mode 1560 when the distance is equal to, substantially equal to, or less than the radius of the second circular trajectory 1556. This switching routine may also be expressed as the following equation:

$\text{onCircleTwo}(x, T, \phi^x, \phi^T) = \|C^T - x\| \leq \epsilon$ , where  $\epsilon$  may be configurable to equal or substantially equal the radius of second circular trajectory 1556.

Once it is determined that the trailer 110 has reached the tangent position and the trajectory planner 1550 switches to the second operating mode 1560, the second operating mode 1560 is processed to guide the trailer 110 to the waypoint position. Given the tangent orientation of the tangent position relative to the second circular trajectory 1556, as shown in FIG. 68, the second operating mode 1560, according to one embodiment, may guide the trailer 110 to the waypoint position without considering the angular orientation of the waypoint position. Specifically, the trailer's orientation at the tangent position will be inherently tangent to the second circular trajectory 1556. Therefore, the second operating mode 1560 may continue to guide the trailer in tangent orientation to the second circular trajectory 1556 along the arc length  $\partial C^T$  to reach the coordinate location of the waypoint position in the substantially correct angular orientation of the waypoint position, irrespective of processing the angular orientation of the waypoint position. This simplified process of the second operating mode 1560 compared with the first operating mode 1558 may be done with less processing requirements and other conceivable benefits. However, it is understood that the second operating mode 1560, in an additional embodiment, may also guide the trailer 110 to the

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waypoint position considering the angular orientation, like the first operating mode 1558.

With further reference to FIG. 68, the second operating mode 1560 assumes the path will be circular and have a tangent that is collinear with the trailer orientation. Accordingly, the center point of the circle can be found with computing the following equation:

$$c^x = (c_1^x, c_2^x) = \left( x_1 - \frac{\sin(\phi^x)}{\kappa^x}, x_2 + \frac{\cos(\phi^x)}{\kappa^x} \right).$$

Upon derivation, the desired curvature  $\kappa_2$  provided by the second operating mode 1560 of the trajectory planner 1550 may be provided as follows:

$$\text{circle}(x, T, \phi^x) = 2 \frac{(T_1 - x_1)\sin(\phi^x) - (T_2 - x_2)\cos(\phi^x)}{(T_1 - x_1)^2 + (T_2 - x_2)^2}.$$

Referring again to FIG. 65, the trajectory planner 1550, according to one embodiment, may include an additional operating mode, such as a projection mode 1576, that is configured to guide the trailer 110 substantially straight to the waypoint position if the trailer 110 becomes generally collinear with the waypoint position at any point during the first or second operating modes 1558, 1560. Stated differently, the projection mode 1576 may provide curvature  $\kappa_2$  outputs when the waypoint position is generally straight behind and nearly in the same angular orientation as the trailer 110 in the current position. As such, the projection mode 1576 may be provided to prevent unnecessary curvature  $\kappa_2$  outputs when simply guiding the trailer 110 straight rearward would reach the waypoint position.

The trajectory planner 1550 may begin to process the projection mode 1576, in one embodiment, from both the first and second operating modes 1558, 1560, such that the projection mode 1576 may include a projection-switch routine to either be processed separate from and contemporaneously with the first and second operating modes 1558, 1560, or integrally processed as part of each operating mode. In one embodiment, the projection-switch routine may become true when the waypoint position falls within a cone threshold of the trailer 110, along with the angles lining up, which may be mathematically expressed as:

$$\text{ProjectionSwitch}(x, T, \phi^x, \phi^T) =$$

$$\left\| \tan^{-1} \left( \frac{T_2 - x_2}{T_1 - x_1} \right) - \phi^x \right\| < \epsilon_1 \wedge \|\phi^x - \phi^T\| < \epsilon_2.$$

To establish the distance and orientation of the waypoint position relative to the current position of the trailer 110, an offset vector may be defined as  $\psi = T - x$ . In addition, a rotation matrix from the coordinate system of the state estimator 1552 to the frame of the trailer 110 may be expressed as follows:

$$\text{rot}(\phi^x) := \begin{bmatrix} \cos(\phi^x) & -\sin(\phi^x) \\ \sin(\phi^x) & \cos(\phi^x) \end{bmatrix}.$$

Accordingly, the offset vector in the trailer reference frame may be expressed as follows:

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$\psi^T = \text{rot}(\phi^x)\psi$ , which represents where the trailer 110 is relative to the orientation of the trailer 110. A scale factor  $k^p$  may be provided for tuning, which thereby defines the curvature  $\kappa_2$  output provided by the projection mode 1576 of the trajectory planner 1550 as follows:

$$\text{projection}(x, T, \phi^x, \psi^T) := k^p * \psi_2^T.$$

The input provided may also be interpreted as the scaled lateral offset of the waypoint position with respect to the trailer heading.

In operation, as shown in FIG. 69, the trajectory planner 1550 provides the desired curvature  $\kappa_2$  to the curvature controller 1508 for the vehicle 100 to guide the trailer 110 from the current position to the waypoint position. In the illustrated simulation, the current position has an angular orientation ninety degrees offset from the waypoint position. As such, the trajectory planner 1550 processed the first operating mode 1558 with the cost function to generate the first and second circular trajectories 1554, 1556 generally depicted, whereby the first circular trajectory 1554 has a substantially smaller curvature than the second circular trajectory 1556. Once the trailer 110 reached the tangent position, X, the trajectory planner 1550 switched to the second operating mode 1560 and guided the trailer 110 along a substantially constant curvature to the location of the waypoint position. As can be seen in operation, the trailer 110 may not exactly follow the first and second circular trajectories 1554, 1556 that are initially calculated at a starting point 1577, which could look more similar to those shown in FIG. 66. This is due to the trajectory planner 1550 dynamically regenerating the first and second circular trajectories 1554, 1556 to account for the trailer's actual path of travel deviating from the path initially generated at the starting point 1577. This may result in a path of travel having a curved shaped that does not correlate with two distinct circular trajectories. This characteristic is also shown in the potential paths generated in FIGS. 67A-67B.

Referring now to FIG. 70, the planner modes of an additional embodiment of the trajectory planner 1550 are illustrated in a flow diagram to account for a waypoint module 1572 (FIG. 63) that includes a plurality of waypoints, which also each include a coordinate location and an angular orientation. Similar to the planner modes 1564 shown in FIG. 65, a first operating mode 1558 is included to generate the first and second circular trajectories 1554, 1556 tangent to one another connecting between the current position and a waypoint of the plurality of waypoints. Again, the first mode 1558 dynamically regenerates the first and second circular trajectories 1554, 1556 as the trailer 110 reverses on the first circular trajectory 1554 to a tangent position between the first and second circular trajectories 1554, 1556. Also, a second operating mode 1560 dynamically regenerates the second circular trajectory 1556 as the trailer 110 is guided to the waypoint position along the second circular trajectory 1556. As with the other features described with reference to the planner modes 1564 shown in FIG. 65, the second operating mode 1560 of the planner modes 1564 shown in FIG. 70 may generate the second circular trajectory 1556 independent of the angular orientation at the waypoint. The embodiment shown in FIG. 70 also includes a projection mode 1576 that may operate with the first and second operating modes 1558, 1560 as described above.

As also shown in FIG. 70, a third operating mode 1562 may be included that switches to the first operating mode 1558 when the trailer 110 reaches the waypoint for guidance to a subsequent waypoint of the plurality of waypoints. This may occur when either the second operating mode 1560 guides the trailer 110 to the waypoint or the projection mode 1576 guides the trailer 110 to the waypoint. It is contemplated that the plurality of waypoints may be ordered, such that the third operating mode 1562 determines the subsequent waypoint as

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the next sequential waypoint provided in a list of waypoints. However, it is also conceivable that the third operating mode 1562 may determine the subsequent waypoint based on the proximity of the plurality of waypoints relative to the current position of the trailer 110 when reaching the waypoint guided by the second operating mode 1560 or the projection mode 1576.

Still referring to the embodiment illustrated in FIG. 70, a fourth operating mode 1578 is depicted that that is configured to stop the vehicle 100 and the trailer 110 when the trailer 110 reaches or substantially reaches a final waypoint of the plurality of waypoints. Again, in one embodiment, the final waypoint may be the last waypoint sequentially in a list of waypoints. As such, the fourth operating mode 1578 determines when the trailer 110 substantially reaches the final waypoint, such as overcoming a threshold distance between the current position and the final waypoint, whereby the threshold distance may be adjusted based on the degree of accuracy desired for the system. When the fourth operating mode 1578 determines that the final waypoint has been reached by the trailer 110, the trajectory planner 1550 may communicate directly or via the curvature controller (FIG. 62) to the vehicle 100 to effectively stop the trailer 110, such as by reducing the throttle of the vehicle's engine, braking with the vehicle brake system or the trailer brake system, engine braking, or otherwise reducing the velocity of the trailer 110 and vehicle 100 to stop the backing maneuver of the trailer 110.

As illustrated in FIG. 71, a simulated path of the trailer 110 is defined for one embodiment of the trajectory planner 1550 having the operating modes illustrated in FIG. 70. In the illustrated embodiment, the plurality of waypoints included thirteen waypoints sequentially ordered with an initial waypoint 1580, intermediate waypoints 1582, and a final waypoint 1584. In one embodiment, the plurality of waypoints may be provided to generate a path that would otherwise not be generated if only a single (final) waypoint was provided. Accordingly, it is contemplated that the path generated between the plurality of waypoints may be configured to avoid an obstacle between an initial waypoint and the final waypoint. Such an obstacle may include a navigating around a sharp corner or a building or may also include navigating along a narrow roadway or through a bottleneck region of a path or a congested parking lot.

To provide the guidance of the trailer, as shown in FIG. 71, between the plurality of waypoints, the trajectory planner 1550 provided a desired curvature  $\kappa_2$  to the curvature controller (FIG. 62) based on the curvature  $\kappa_2$  of the projected trajectory that the trailer 110 was traveling over. For instance, when the trailer 110 was on a first circular trajectory 1554 as projected by the first operating mode 1558, the radius of the first circular trajectory 1554 is used to provide the desired curvature  $\kappa_2$  to the curvature controller 1508, and likewise, when the trailer 110 was on a second circular trajectory 1556, as projected by the second operating mode 1560, the radius of the second circular trajectory 1556 is used to provide the desired curvature  $\kappa_2$  to the curvature controller 1508. To offer additional explanation, FIGS. 72A-B are provided to show the desired and measured curvatures as well as the planner mode that were used when operating the trajectory planner 1550 for reversing the trailer along the simulated path shown in FIG. 71. As such, the time interval is identical between FIGS. 72A-B, so it can be observed how the change in desired curvature  $\kappa_2$  correlates with the change in planner modes.

It is to be understood that variations and modifications can be made on the aforementioned structure without departing from the concepts of the present invention, and further it is to



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be understood that such concepts are intended to be covered by the following claims unless these claims by their language expressly state otherwise.

What is claimed is:

1. A trailer backup assist system comprising:
  - a state estimator determining a current position of a trailer relative to a plurality of waypoints;
  - a trajectory planner for incrementally generating a path from the current position to the plurality of waypoints, comprising:
    - a first mode generating first and second circular trajectories tangent to one another connecting between the current position and a waypoint of the plurality of waypoints;
    - a second mode generating the second circular trajectory between the current position and the waypoint after the trailer traverses the first circular trajectory; and
    - a third mode switching to the first operating mode when the trailer reaches the waypoint for guidance to a subsequent waypoint of the plurality of waypoints; and
  - a curvature controller guiding the trailer based on a curvature of the respective first or second circular trajectories.
2. The trailer backup assist system of claim 1, wherein the first mode dynamically regenerates the first and second circular trajectories as the trailer reverses on the first circular trajectory.
3. The trailer backup assist system of claim 1, wherein the plurality of waypoints each include a coordinate location and an angular orientation, and wherein the second mode generates the second circular trajectory independent of the angular orientation at the waypoint.
4. The trailer backup assist system of claim 1, wherein the first mode stops and the second mode begins to generate the second circular trajectory when the trailer reaches a position tangent to both the first and second circular trajectories.
5. The trailer backup assist system of claim 1, wherein the curvature controller generates a steering angle command for a vehicle towing the trailer as a function of a hitch angle between the vehicle and the trailer, a steering angle of the vehicle, and the curvature of the respective first or second circular trajectory that the trailer is on.
6. The trailer backup assist system of claim 1, wherein the plurality of waypoints includes a final waypoint, whereby the trajectory planner includes a fourth mode for stopping the trailer when the trailer reaches the final waypoint.
7. The trailer backup assist system of claim 6, wherein the path between the plurality of waypoints is configured to avoid an obstacle between an initial waypoint and the final waypoint.
8. The trailer backup assist system of claim 7, wherein the state estimator includes a positioning device that generates a localized coordinate system that encompasses the plurality of waypoints.
9. A trailer backup assist system, comprising: a trajectory planner comprising:
  - a first mode generating first and second of circular trajectories tangent to one another connecting between a current position of a trailer and a waypoint of a plurality of waypoints;
  - a second mode generating the second circular trajectory to the waypoint; and
  - a third mode switching to the first operating mode at the waypoint if the plurality of waypoints includes a subsequent waypoint; and

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a controller guiding the trailer based on the first and second circular trajectories.

10. The trailer backup assist system of claim 9, wherein the first mode dynamically regenerates the first and second circular trajectories as the trailer reverses on the first circular trajectory.

11. The trailer backup assist system of claim 9, wherein the trajectory planner further comprises:

a fourth mode stopping the trailer when the trailer reaches a final waypoint of the plurality of waypoints.

12. The trailer backup assist system of claim 9, wherein the plurality of waypoints each include a coordinate location and an angular orientation.

13. The trailer backup assist system of claim 12, wherein the second mode generates the second circular trajectory once the trailer traverses the first circular trajectory and independent of the angular orientation at the waypoint.

14. The trailer backup assist system of claim 9, wherein the second mode begins to generate the second circular trajectory when the trailer reaches a position tangent to both the first and second circular trajectories.

15. The trailer backup assist system of claim 9, wherein the controller comprises a curvature controller that guides the trailer based on a curvature of the first circular trajectory in the first mode and of the second circular trajectory in the second mode.

16. The trailer backup assist system of claim 15, wherein the curvature controller generates a steering angle command for a vehicle towing the trailer as a function of a hitch angle between the vehicle and the trailer, a steering angle of the vehicle, and the curvature.

17. A method for reversing a trailer between a plurality of waypoints, comprising:

generating with a processor first and second circular trajectories tangent to one another connecting between a current position of the trailer and a first waypoint of the plurality of waypoints;

guiding with a controller the trailer along the first circular trajectory while regenerating the first and second circular trajectories;

guiding with the controller the trailer along the second circular trajectory to the first waypoint while regenerating the second circular trajectory;

generating with the processor third and fourth circular trajectories tangent to one another connecting between the current position and a second waypoint of the plurality of waypoints;

guiding with the controller the trailer along the third circular trajectory while regenerating the third and fourth circular trajectories; and

guiding with the controller the trailer along the fourth circular trajectory to the second waypoint.

18. The method of claim 17, further comprising: determining the current position of the trailer relative to the plurality of waypoints.

19. The method of claim 17, wherein the plurality of waypoints each include a coordinate location and an angular orientation, and wherein the second circular trajectory is dynamically regenerated independent of the angular orientation of the first waypoint.

20. The method of claim 17, further comprising: switching from guiding the trailer along the first circular trajectory to guiding the trailer along the second circular trajectory when the trailer reaches a tangent position between the first and second circular trajectories.

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